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Can rewards enhance creativity? Exploring the effects of real and hypothetical rewards on creative problem solving and neural mechanisms

Can Cui[1], Yuan Yuan[2] and Yingjie Jiang[2*]

Abstract

Reward cues have long been considered to enhance creative performance; however, little is known about whether rewards can affect creative problem solving by manipulating states of flexibility and persistence. This study sought to elucidate the differential impacts of real versus hypothetical rewards on the creative process utilizing the Chinese compound remote association task. Behavioral analysis revealed a significantly enhanced solution rate and response times in scenarios involving real rewards, in contrast to those observed with hypothetical rewards. Electrophysiological findings indicated that hypothetical rewards led to more positive P200-600 amplitudes, in stark contrast to the amplitudes observed in the context of real rewards. These findings indicate a positive impact of real rewards on creative remote associations and contribute new insights into the relationship between rewards and creative problem solving, highlighting the crucial role of persistence/flexibility in the formation of creativity.

Keywords Creative problem solving, P200-600, Insight, Metacontrol state, Reward

Introduction

Creativity, a profound and intricate phenomenon of the human mind [69], serves as the wellspring of human civilization by fostering the creation of knowledge and artifacts that are integral to human culture. Consequently, enhancing creative performance emerges as a critical objective within creativity research. Historically, creativity has been predominantly assessed through divergent thinking tasks, which involve generating multiple novel solutions to open-ended problems [7]. However, divergent thinking is not entirely synonymous with creativity, and convergent thinking also constitutes a vital component of creativity [58]. Creative cognition engages both an initial divergent (i.e., generative) process, wherein the representational space is expanded during broad memory search, and a later convergent (i.e., evaluative) process, involving the narrowing down of alternatives to a single response [42, 61]. Convergent thinking usually involves solving ill-defined problems that often require a reframing of task representations [7, 40, 42]. The Remote Associates Test (RAT) devised by Mednick [48] is now primarily thought to engage convergent thinking because it requires "converging" on the single correct solution [40]. The compound remote associates (CRA) test is a modern variation of the RAT, designed to illicit both insightful and analytical problem solving strategies [10, 11, 37, 42, 68]. Each problem in the CRA task consists of three words (e.g. pine, crab, and sauce), and the participant is required to think of a single solution word (apple)

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*Correspondence:
Yingjie Jiang
jiangyj993@nenu.edu.cn
[1] Jiangsu Key Laboratory of Brain Disease and Bioinformation, Xuzhou Medical University, Xuzhou 221004, China
[2] School of Psychology, Northeast Normal University, 5268 Renmin Street, Changchun 130024, Jilin, China

that can form a familiar phrase with each word (pineapple, crab apple, and apple sauce). These hybrid-type problems can be solved through insight or through analytic processes, with participants on each successful trial required to report which of the two most contributed to problem solving [11, 35]. The CRA is well-suited for EEG and neuroimaging research due to its use of brief timing epochs and the availability of numerous normed task items, which persistence and flexibility are associated with dopamine activity allow for well-powered experimental designs. This has contributed to the widespread use of CRA in cognitive and brain-based studies, particularly for examining the convergent thinking component of creative problem solving [6]. Therefore, the present study specifically focused on how to improve creative problem solving by using the CRA task.

The CRA task is particularly relevant as it provides a nuanced assessment of creative problem-solving, capturing both insight and analytical processes [69], which are crucial for understanding cognitive flexibility and persistence. In creativity research, numerous studies have identified two distinct cognitive pathways that contribute to the emergence of creativity [1, 17, 19, 59, 65, 69]. The first pathway, flexible thinking, involves exploring a broad range of categories and perspectives, whereas the second pathway, persistent thinking, entails a focused and effortful examination of a limited number of cognitive categories and perspectives. Both pathways have been shown to generate creative outcomes, as outlined in the dual pathway to creativity model [4]. Flexible thinking facilitates access to distant information and enables the discovery of novel connections between categories and concepts. In contrast, persistent thinking supports systematic, effortful, and incremental search processes [20, 24, 51, 65]. According to the Metacontrol State Model (MSM, a model that was conceived to account for cognitive control in general, but that can be easily applied to creativity), the behavior emerges from a balance between persistence and flexibility [32]. Extreme persistence would consist in strong mutual competition as well as top-down bias, whereas extreme flexibility would consist in weak competition and weak top-down bias [32, 69]. A relatively high level of goal-directed cognitive control promotes persistence, while a relatively low level of cognitive control leads to a more flexible state. Available evidence strongly suggests that persistence and flexibility are associated with dopamine activity [9, 69]. Increasing evidence also indicates that creative cognition is influenced by dopaminergic modulation in fronto-striatal brain circuits. Specifically, persistence and flexibility in creative cognition are modulated by prefrontal dopamine and striatal dopamine, respectively [69]. For example, previous research has suggested that elevated dopamine levels may foster creativity by reducing inhibition of alternative thoughts and increased cognitive flexibility [16, 17]. Dopamine neurons are well known for their strong responses to rewards and their critical role in positive motivation [12]. In general, available evidence strongly suggests that frontal and striatal dopaminergic pathways play a crucial role in human creativity by regulating cognitive persistence and flexibility [69]. Therefore, reward as a common motivator in real life, may affect creative problem solving by affecting the persistence/flexibility pathways.

Creative problem solving is inherently rewarding, particularly when individuals solve problems through insight, with one electrophysiological study indicating that insight-related effects are modulated by reward sensitivity [52]. However, attempts to facilitate creative problem solving via external reward have so far been unsuccessful and controversial [2, 16, 26], although evidence suggests that monetary incentives can enhance behavioral performance [53]. Indeed, whether rewards have an impact may depend on their category, and different categories of rewards may cause differential changes in control processes and thus have different impacts on creative problem solving. For example, people could solve higher percentage of CRA problems and achieved more insight solution under subliminal rewards condition, compared with supraliminal rewards [16, 17]. These findings are based on the awareness dimension; however, manipulating awareness levels in a laboratory setting is challenging to apply in real-life situations. To meaningfully apply laboratory results to real-life contexts, it is crucial to select reward conditions that are more compatible. Many studies in experimental psychology and economics compare hypothetical rewards to real rewards [13]. Contrary to real rewards, which offer concrete benefits, hypothetical rewards are devoid of such tangible advantages. Previous studies have shown that when participants were receiving real rewards during the discounting tasks, their choices were more self-controlled [29], real and hypothetical rewards elicit differences in levels of cognitive control. Consequently, real rewards are anticipated to augment cognitive control to a higher degree, fostering increased persistence compared to hypothetical rewards. It is therefore hypothesized that real rewards will enhance cognitive control to a greater extent, promoting increased persistence relative to hypothetical rewards. The metacontrol of human creativity theory indicates that creative cognition in convergent, analytical thinking tasks (RAT type task) seem to benefit from persistence, whereas insight and divergent thinking seems to benefit from flexibility [49, 69].

In the present study, we used Chinese CRA paradigm to investigate the effect of real/hypothetical rewards to creative performance. Compared with hypothetical rewards, real rewards have a higher level of cognitive control, therefore we hypothesized that real reward could have a higher solution rate of the CRA task, and hypothetical rewards may have a higher insight rate. In addition to the type of reward, the level of reward often affects creative performance as well. Speed-accuracy trade-offs tend to be affected only when individuals are aware of the reward [8], the size and awareness of reward could modulate problem solving [16]. Participants generally exert more mental effort on a cognitive control task when they are offered greater rewards for performing well [28]. Therefore, based on the previous reward related research [16, 17], this study also investigated the effects of different rewards levels on creative problem-solving performance, and we hypothesized that the low rewards have a higher solution of the CRA task.

To gain a more comprehensive understanding of the impact of rewards on creative problem solving, it is essential to incorporate neurophysiological measures or neuroimaging techniques [16]. Behavioral measures alone are insufficient to provide conclusive evidence regarding the cognitive control and attentional processes involved in creative problem solving. This study addresses this issue by employing electrophysiological techniques with high temporal resolution. Creative problem solving, as evaluated by the compound remote association (CRA) test, can be approached through both noninsight (i.e., analytic) and insight solutions, insight solutions can be generated either by external stimuli or internal solution attempts, namely, “induced” or “spontaneous” insight [17, 18, 36, 45, 55, 57, 57, 64]. In spontaneous insight paradigms, the participants find the solution independently, and in induced insight paradigms, the experimenter gives the participants the answer to induce an “Aha!” experience. The cognitive process of spontaneous insight differs from that of induced insight [55], previous studies have suggested that creative insight (induced) generally elicited greater N2 or N400 component, while spontaneous insight was associated with the P200–600 component [17, 47, 54, 55, 63]. In addition, the early ERP components, such as frontal N1 associated with attentional allocation may contribute to creative perception stage [71], and Chinese logogriphs solved successful also could induced N1 component in the early time, therefore, the current study examining the effects of rewards on creative problem solving by these electrophysiological indices.

Taken together, the aim of the present study was to investigate differential effects of real and hypothetical monetary rewards on creative problem solving in the temporal dimension. We used the Chinese verbal CRA test to explore the impact of monetary rewards on creative problem solving. To avoid any misconceptions, notably, in the present study, we used a spontaneous insight paradigm in which the participants independently found the solution. Based on previous studies [16, 17, 35, 55, 71], we focused on the potential effects at approximately 200 to 600 ms (P200–600), and N1 component after the problem onset on the solving process. Available evidence indicates that the P200-600 component observed in the parietal region during insight problem-solving paradigms may correspond to the P300 component [17, 55]. In creativity research, the P300 component may reflect the formation of novel and rich associations (schema induction) based on heuristic information retrieval [55]. The amplitude of the P300 has been linked to cognitive flexibility [23, 39, 62]. A study by Cui et al. [17] indicated that subliminal rewards can induce a more positive P200-600 component, potentially reinforcing cognitive flexibility without increasing attentional selectivity [16]. These findings suggest that greater cognitive flexibility is associated with a higher P200-600 amplitude. Therefore, based on the higher cognitive flexibility of hypothetical reward, we predicted that the hypothetical rewards would induce a greater P200–600 amplitude compared to real rewards. Additionally, N1 is associated with early attentional selection [67]. Frontal N1 has been linked to the automatic attentional response to novel features [71], and it serves as an indicator of cognitive sensitivity to creative information [70]. Furthermore, N1 has been associated with the early stages of visual processing [55]. Therefore, we also speculated that the N1 component would be induced by the early stage of creative problem solving.

Methods

Participants

We conducted total sample size estimation by G*Power to determine the number of participants sufficient to detect a reliable effect. According to partial eta square values of previous reward-creative problem solving studies [16, 18], we calculate the effect size f are 0.47 and 0.52. Consequently, we adopted an effect size of $f=0.4$, as suggested by Cohen [15], 20 participants were needed to detect a significant effect ($\alpha=0.05$, power $(1-\beta)=0.9$, ANOVA: repeated measures, 2×2 within factors, G-Power 3.1.9.2) [27].

Twenty-five participants aged 18 to 23 years ($M=20.74$, $SD=1.51$; women: 22) participated in this study. All participants had normal or corrected-to-normal vision, were unaware of the study’s aims, and were right-handed native Chinese speakers with no reported neurological disorders. The study received approval from the local ethics committee. Upon completion, participants were thoroughly informed about the study's objectives and procedures. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Participants received 50￥as payment for their participation, with additional monetary rewards paid (up to 70￥) depending on their performance.

Design and procedure

The stimuli were presented on a CRT monitor with a resolution of 1920×1080 and a refresh rate of 85 Hz. The experiment was programmed using E-Prime 3.0 (Psychology Software Tools, Inc., Pittsburgh, PA, USA) for both stimulus presentation and response recording. The study employed a within-subjects design with a 2 (reward type: real or hypothetical)×2 (reward level: high or low) factorial structure. Participants were provided with detailed instructions regarding the reward conditions, the Chinese CRA task, and the concept of insight. They then completed five practice trials to familiarize themselves with the task.

As illustrated in Fig. 1, each trial began with a central fixation cross displayed for 0.5 s, followed by the presentation of a reward value (**1￥/0.1￥**, presented in half of the trials) for 1 s. Participants were subsequently required to solve Chinese CRA problems [18, 25]. Each problem in the Chinese CRA task consisted of three stimulus words (e.g., "xing/liu/li", 行, 流, 里) presented together. Participants had to generate a solution word (e.g., "cheng", 程) that could combine with each of the three given words to form a familiar two-word phrase (i.e., "xing cheng", 行程, "liu cheng", 流程, "li cheng", 里程) within a 10-s time limit. Once participants found a solution, they were instructed to press the space key immediately. The correct answer was then presented, and participants had 3 s to judge whether their answer matched the given solution (participants were informed of the importance of honesty in their responses). Subsequently, participants were prompted to press the "F" or "J" key within 3 s to indicate whether the solution was reached through insight or non-insight [35, 60]. Pressing the "F" key indicated that the solution was achieved through insight, while pressing the "J" key indicated no insight. Participants were asked to respond using the index fingers of both hands [18]. All buttons press assignments were counterbalanced across participants. Successful problem solving was followed by reward feedback. In the hypothetical reward condition, participants were informed that the gains were virtual and were instructed to imagine them as real money, striving to maximize their virtual profits. Conversely, in the real reward condition, participants were informed that the rewards earned during the experiment were tangible, with the assurance that their compensation would be directly proportional to the actual monetary gains they accumulated throughout the study. The experiment consisted of two blocks: real and hypothetical rewards, with the blocks counterbalanced across participants. Within each block, all items were pseudo randomly assigned to two reward levels. The entire experiment comprised 240 trials. All trials were presented randomly to the participants, and after the participants completed 60 trials, they could rest. After participants completed the experiment, we asked them whether they perceived a difference in the size of the two rewards by informal verbal question, and they all confirmed that they did. The specific procedure of the experiment is shown in Fig. 1.

EEG recording and analysis

EEG data were collected during the Chinese CD task using the Neuroscan Synamps2 EEG recording and

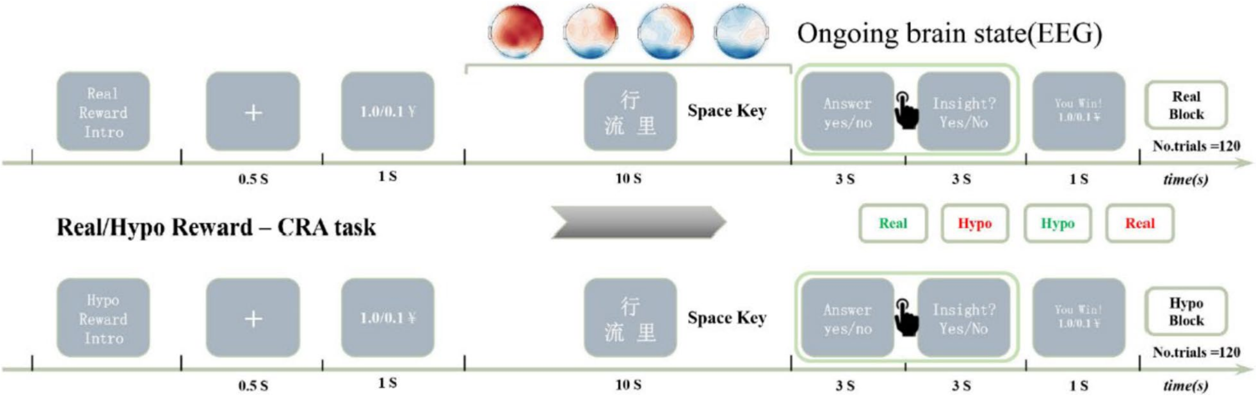

Fig. 1 The procedures of Experiment 1. Real Block: real reward condition; Hypo Block: hypothetical reward condition. CRA: compound remote associate. The experiment consisted of two blocks: real and hypothetical rewards, with the blocks counterbalanced across participants

analysis system. EEGs were recorded using 64 Ag/AgCl electrodes in an elastic cap using the International Standard 10–20 system. Vertical and horizontal EEGs were recorded during data acquisition using the Neuroscan electrode cap and with its own reference electrode as the online reference electrode. EEG data were sampled at 1000 Hz/channel, electrode impedances were kept lower than 10 kΩ, and the recording bandwidth ranged from 0.05 to 100 Hz.

Off-line analyses were performed in MATLAB using the EEGLAB toolbox [21] and ERPLAB toolbox [41]. The EEG signals were referenced to the average of bilateral mastoid electrodes and filtered using IIR-Butterworth filters with half-power cutoffs at 0.1 Hz (roll-off = 12 dB/oct) with a high-pass filter and at 30 Hz (roll-off = 12 dB/oct) with a lowpass filter [43]. Independent component analysis (ICA) was performed to correct the components associated with eve movement and eye-blink artifacts. Then, the artifact correction process was supplemented with artifact rejection to eliminate the trials with clearly artifactual voltage deflections. Specifically, trials were excluded if the peak-to-peak voltage within the EEG epoch was greater than 300 μV in any 200 ms window in any channel [5]. Four participants were excluded for whom > 35% of trials were rejected because of EEG/EOG artifacts; therefore, 21 participants were included in the ERP/EEG analysis. EEG data were segmented into epochs. The problem-solving phase was segmented into epochs using a time window of 1400 ms, ranging from 200 ms before the stimulus to 1200 ms after the stimulus. For each subject, epochs belonging to the same reward condition were averaged, yielding four average waveforms time locked to the stimulus onset. Single-subject average waveforms of each reward condition were averaged across subjects to obtain group-level waveforms. Based on previous creative EEG studies [17, 55, 71] and grand average waveforms, we focused on the P200-600 component and N1 component. To increase statistical strength and reduce false effects [44], the F3, Fz, and F4 electrodes were collapsed by averaging their values as an indication of frontal activity; the FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, and P4 electrodes were collapsed by averaging their values as an indication of frontocentral, central, centroparietal and parietal activity, respectively. Three-factor repeated measures ANOVAs with 2 (reward: real, hypothetical) × 2 (level: high, low) × 5 (region: frontal, frontocentral, central, centroparietal, parietal) factors were used.

For behavioral measures and ERP components, we utilized JASP 16.1 software [66]. In all analyses, we employed the Greenhouse–Geisser method to correct the p values of the F tests for deviations. The effects of ANOVAs were measured using partial eta squared, referred to as η_p^2. For effect sizes in paired t tests, we employed Cohen's d, which calculates the mean difference score as the numerator and the pooled standard deviation from both repeated measures as the denominator [15]. To address multiple comparisons, we applied the Holm correction [30] in the present research.

Results

Behavioral performance

The participants correctly solved 47.4% (SD = 6.6%) of the problems. When considering real reward conditions, 50.8% (SD = 10.1%) of the problems were solved under high reward conditions, while 51.8% (SD = 8.8%) were solved under low reward conditions. The average response times were 4.54 s (SD = 0.67 s) for the high-reward condition and 4.36 s (SD = 0.67 s) for the low-reward condition. In the hypothetical conditions, 41.6% (SD = 7.7%) of the problems were solved under the high reward condition, and 45.4% (SD = 8.4%) were solved under the low reward condition. The average response times were 4.78 s (SD = 0.69 s) for the high-reward group and 4.71 s (SD = 0.54 s) for the low-reward group (Table 1).

The solution rate, response times, and insight rate were analyzed using a repeated-measures ANOVA with a 2 (reward: real vs. hypothetical) × 2 (level: high vs. low) design. As shown in Fig. 2, we observed a significant main effect for the reward condition, F (1, 20) = 20.71, $p < 0.001$, $\eta_p^2 = 0.51$. Post hoc comparisons indicated that participants solved more CRA items under real rewards, t (20) = 4.55, $p < 0.001$, Cohen's $d = 0.89$. Furthermore, participants exhibited a greater ability to solve CRA items under low rewards than under high rewards, t (20) = 2.04, $p = 0.055$, Cohen's $d = 0.28$, although the effect of level did not reach significance, F (1, 20) = 4.16, $p = 0.055$, $\eta_p^2 = 0.17$. No significant interaction effect was observed, F (1, 20) = 0.87, $p = 0.36$, $\eta_p^2 = 0.04$.

For average response times, the ANOVA showed a significant main effect for the reward condition, F (1, 20) = 8.93, $p = 0.007$, $\eta_p^2 = 0.31$, but no significant main effect was observed for the reward level and interaction effect, F (1, 20) = 2.13, $p = 0.16$, $\eta_p^2 = 0.10$; F (1, 20) = 0.44, $p = 0.51$, $\eta_p^2 = 0.02$. Post hoc comparisons indicated that

Table 1 Means and SDs of the solution rate, average response times and insight rate

Measure	Real reward		Hypothetical reward	
	High	Low	High	Low
Solution rate	0.51 ± 0.10	0.52 ± 0.09	0.42 ± 0.08	0.45 ± 0.08
RT(s)	4.54 ± 0.67	4.36 ± 0.67	4.78 ± 0.69	4.71 ± 0.54
Insight rate	0.51 ± 0.29	0.49 ± 0.28	0.45 ± 0.32	0.47 ± 0.34

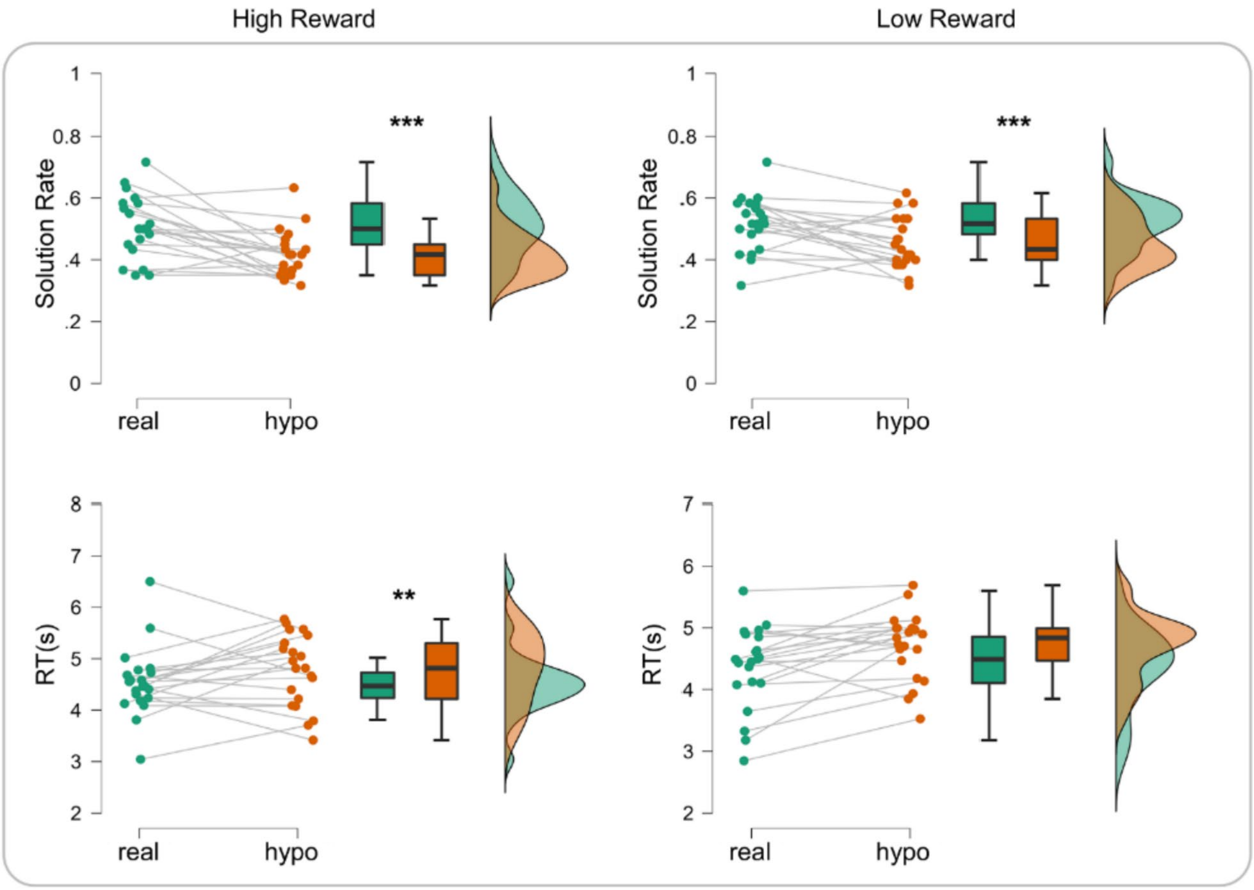

Fig. 2 The behavioral performance in the CRA task. There was a significant difference between the solution rate of real rewards and hypothetical rewards; There was a significant difference between the reaction times of real high rewards and hypothetical high rewards $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$

participants responded significantly faster to real rewards than to hypothetical rewards (Fig. 2), $t\ (20) = -\ 2.99$, $p = 0.007$, Cohen's $d = 0.45$. For the insight rate, there was no significant main effect of reward type, $F\ (1, 20) = 0.91$, $p = 0.35$, $\eta_p^2 = 0.04$, or reward level, $F\ (1, 20) = 0.04$, $p = 0.85$, $\eta_p^2 = 0.002$, and no significant interaction effect, $F\ (1, 20) = 1.19$, $p = 0.29$, $\eta_p^2 = 0.06$.

ERP analysis

N1 (120–180 ms)

To examine whether there were differences in N1 (120–180 ms) between different reward conditions for CRA processing, a 2 (reward: real vs. hypothetical) × 2 (level: high vs. low) × 5 (region: frontal vs. frontocentral vs. central vs. centroparietal vs. parietal) repeated ANOVA was conducted on the N1 amplitude. There was no significant main effect of reward, $F\ (1, 20) = 2.38$, $p = 0.14$, $\eta_p^2 = 0.11$. The main effects of level were also not significant, $F\ (1,20) = 0.4$, $p = 0.53$, $\eta_p^2 = 0.02$, while the effect of region was significant, $F\ (4, 80) = 7.98$, $p < 0.001$, $\eta_p^2 = 0.29$. No other significant interaction effect was observed (Table 2). Post hoc comparisons revealed more negative waveforms in the central-parietal and parietal regions than in the frontal region ($t\ (80) = 4.24$, $p < 0.001$; Cohen's $d = 0.70$; $t\ (80) = 5.13$, $p < 0.001$; Cohen's $d = 0.84$) (Fig. 3).

P200-600

To examine whether different rewards induce different P200-600 amplitudes in Chinese CRA processing, an

Table 2 Mean amplitudes of different reward conditions in 120–180 ms time windows

Measure	Real reward		Hypothetical reward	
	High	Low	High	Low
Frontal	1.74 ± 3.11	1.97 ± 2.89	1.40 ± 3.77	1.85 ± 2.60
Fronto-central	0.34 ± 3.12	1.02 ± 2.44	0.76 ± 3.22	1.21 ± 2.16
Central	− 0.20 ± 2.32	0.70 ± 1.87	0.73 ± 2.83	0.92 ± 2.01
Centro-parietal	− 1.03 ± 2.85	0.49 ± 2.36	0.22 ± 2.72	0.61 ± 2.32
Parietal	− 0.75 ± 2.79	0.08 ± 2.96	0.08 ± 2.96	− 0.56 ± 3.05

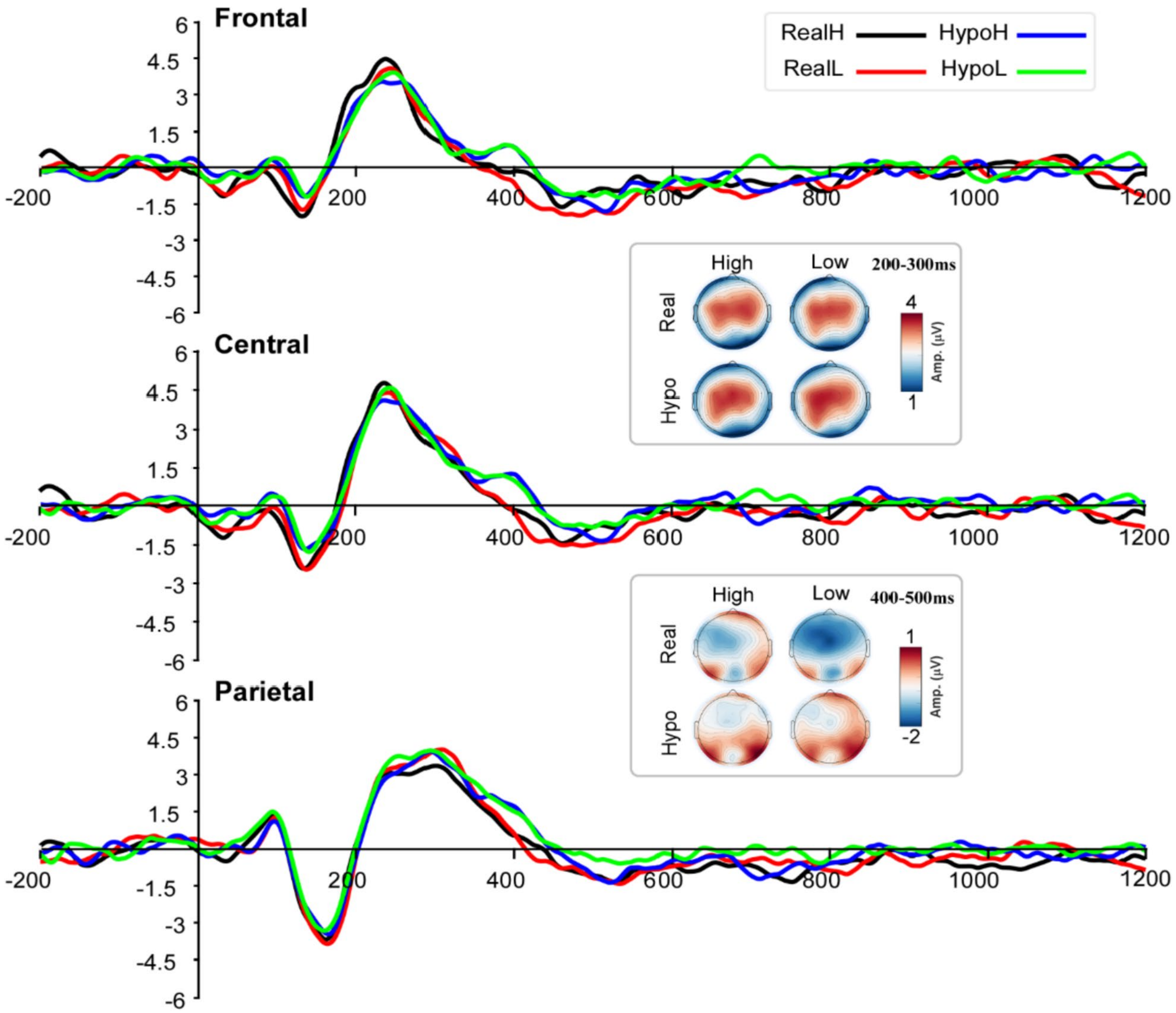

Fig. 3 Event-related potentials (ERPs) in CRA problem solving evoked by different rewards. *RealH* real high rewards, *RealL* real low rewards, *HypoH* hypothetical high rewards; HypoL: hypothetical low rewards

ANOVA of 2 (reward: real vs. hypothetical) × 2 (level: high vs. low) × 5 (region: frontal vs. frontocentral vs. central vs. centroparietal vs. parietal) repeated measures was conducted on P200-600 amplitudes. According to the grand average map (Fig. 3), two bins (220 to 260 ms, 400 to 500 ms) were measured in the CRA solution. The mean amplitudes in the time windows from 220 to 260 ms were measured, and there was no significant main effect of reward, F (1, 20) $= 0.55$, $p = 0.47$, $\eta_p^2 = 0.03$, or level, F (1, 20) $= 0.41$, $p = 0.53$, $\eta_p^2 = 0.02$. There was a main effect of region, F (4, 80) $= 9.31$, $p = 0.002$, $\eta_p^2 = 0.32$. A post hoc test indicated that in the fronto-central brain region, the waveform was significantly greater than that in the centro-parietal and parietal regions, t (80) $= 3.33$, $p = 0.009$, Cohen's $d = 0.36$; t (80) $= 3.70$, $p < 0.001$, Cohen's $d = 0.60$. In the central region, the waveform was significantly greater than that in the parietal region, t (80) $= 4.44$, $p < 0.001$, Cohen's $d = 0.48$. As shown in Fig. 3, the mean amplitudes in the time windows from 400 to 500 ms were measured (Table 3). The results showed that there was a significant main effect of reward, F (1, 20) $= 9.66$, $p = 0.006$, $\eta_p^2 = 0.33$. The main effect of reward level was not significant, F (1, 20) $= 0.46$, $p = 0.50$, $\eta_p^2 = 0.02$. The main effect of region was marginally significant, F (4, 80) $= 3.69$, $p = 0.058$, $\eta_p^2 = 0.16$.

No other interaction effect was observed. Post hoc comparisons showed that hypothetical rewards induced greater amplitude than real rewards, t (20) $= 3.11$

Table 3 Mean amplitudes of different reward conditions in 400–500 ms time windows

Measure	Real reward		Hypothetical reward	
	High	Low	High	Low
Frontal	− 0.95 ± 2.55	− 1.70 ± 2.88	− 0.67 ± 3.28	− 0.55 ± 3.04
Fronto-central	− 1.11 ± 2.36	− 1.72 ± 2.20	− 0.58 ± 2.64	− 0.53 ± 2.25
Central	− 0.90 ± 2.07	− 1.32 ± 1.71	− 0.27 ± 2.22	− 0.28 ± 1.84
Centro-parietal	− 0.55 ± 1.76	− 0.86 ± 1.39	0.05 ± 2.02	0.14 ± 1.69
Parietal	− 0.40 ± 1.81	− 0.58 ± 1.53	0.12 ± 2.08	0.31 ± 1.70

$p = 0.006$, Cohen's $d = 0.35$. The amplitudes in the parietal region were greater than those in the frontal region, t $(80) = 2.99$ $p = 0.037$, Cohen's $d = 0.38$.

Discussion

In this study, we utilized a Chinese CRA task to examine the neurobiological and behavioral mechanisms underlying the impact of real and hypothetical rewards on creative problem solving. To the best of our knowledge, this is the first electrophysiological investigation aimed at elucidating the neural mechanisms involved in the effects of real and hypothetical rewards on CRA problem solving. We obtained two principal findings from this study. Behaviorally, participants solved a greater number of Chinese CRA problems when motivated by real monetary rewards than when motivated by hypothetical monetary rewards. Additionally, the behavioral results indicated that participants solved Chinese CRA problems more quickly in the real reward condition than in the hypothetical reward condition (Fig. 2). Neurophysiologically, hypothetical rewards elicited a more positive P200-600 amplitude than real rewards during the problem-solving phase. Specifically, within the 400–500 ms time interval, hypothetical rewards generated a more positive waveform than real rewards.

Behavioral findings

Overall, the findings of this study demonstrated that real reward cues, in comparison to hypothetical reward cues, significantly facilitated the solution of CRA problems. According to the metacontrol state model, the solution to the CRA problem may benefit from cognitive persistence [32, 69]. Anderson and colleagues indicated that the important characteristic of CRA problems is that it takes a long time to retrieve a solution if one is retrieved at all. This produces a sustained demand on the retrieval module, while the subgoal module remains unchanged [3]. Anderson's research suggested that cognitive persistence in solving CRA problems may sustain continuous activity within the retrieval module, thereby improving problem-solving performance. Our findings partially indicated that low reward could facilitate the solution of CRA items. This results was in line with previous research [1, 14]. Previous studies indicated that the current dopamine level is related to performance in convergent and divergent thinking, while convergent thinking benefits from a low level, divergent thinking is best with a medium-to-high level [14]. Therefore, participants in the low-reward condition were able to solve more CRA items compared to those in the high-reward condition.

Temporal mechanisms of the effect of rewards on creative problem solving

In this study, the ERP technique was employed to elucidate the electrophysiological differences between the types of reward cues. The scalp ERP data revealed that real reward cues and hypothetical reward cues elicited distinct ERP components during the problem-solving phases.

Analysis of the N1 component revealed that the N1 amplitude for real rewards was more negative compared to hypothetical rewards, although this difference did not reach statistical significance ($p = 0.13$). The N1 component has been linked to early stages of visual processing [55] and attentional allocation during the creative perception stage [71]. The real reward condition may have led to greater cognitive persistence during CRA processing, however, this effect was weak in terms of automated perceptual processes due to the block design in which both real and hypothetical reward cues were presented using the same images during perceptual processing. Thus, although the N1 effect was weak, we believe it partially reflects the idea that real rewards can allocate more sustained attention to creative problem-solving compared to hypothetical rewards, partially supporting our hypothesis that real rewards are more biased toward cognitive persistence.

For the P200-600 component, as illustrated in Fig. 3, both real and hypothetical rewards induced a P200–600 component in the spontaneous insight paradigm [17, 55]. However, hypothetical rewards elicited a significantly more positive P200–600 component than real rewards. The P200-600 component refers to a single component, particularly in the context of insight problem solving [17, 55]. Specifically, Qiu et al. [55] found that P200-600 is a positive waveform between 200 and 600 ms after onset of the target logogriph. P200-600 might be an obvious p300 component, the latency P300 latency is thought to represent the relative duration of multiprocess stimulus evaluation/classification operations, and P300 amplitude reflects the amount of attentional resources employed in a given task [22]. Previous studies have indicated that the P300 are often linked to memory updating, encoding, or retrieval, given their appearance in tasks making demands on stimulus evaluation and memory updating resources. In insight problem solving, P200–600 might reflect forming novel and rich associations (schema induction) based on heuristic information retrieval under the true-matching condition, compared to the false-matching condition [55]. Cui et al. [17] used subliminal/supraliminal rewards and CRA paradigms to investigate the effect of subliminal rewards on CRA performance. The ERP results showed that the subliminal rewards may induced a more positive P200-600 component. The P300 amplitude reflects the amount of attentional resources employed in a given task [22]. Subliminal rewards could reinforce cognitive flexibility without increasing the selectivity of attention [16], while supraliminal rewards are more likely to trigger the inhibition process of potentially interfering with stimuli/thoughts. This could explain why subliminal rewards elicited a more positive P200–600 component than supraliminal rewards. In the present study, the P200-600 significantly existed in the parietal region, the grand average waveform was similar with Cui et al. [17]'s study, we therefore thought that this component might be an P300 component.

Additionally, like previous findings on the effect of subliminal rewards on the creative problem solving [17], the results in the current study showed that hypothetical rewards induced a more positive P200-600 component. Behavior emerges from balance between persistence and flexibility, extreme persistence would consist in strong mutual competition as well as top-down bias, whereas extreme flexibility would consist in weak competition and weak top-down bias [69]. Therefore, we inferred that hypothetical rewards may enhance cognitive flexibility more effectively than real rewards, which are more likely to trigger inhibition processes of potentially interfering stimuli or thoughts. This could explain why hypothetical rewards elicited a more positive P200–600 component than real rewards.

According to MSM theory, solving CRA problems may benefit from cognitive persistence [69]. The important characteristic of the RAT problem is that it takes a long time to retrieve a solution, if one is retrieved at all. This produces a sustained demand on the retrieval module, while the subgoal module remains unchanged [3]. These findings suggest that persistence bias may benefit RAT questions. The RAT provides increasingly tight top-down constraints, and there is only one possible answer per item, suggesting that the task calls for a control state with a strong impact on the goal—a bias toward persistence [32]. Therefore, despite the enhanced cognitive flexibility associated with hypothetical rewards, real rewards still led to a greater number of solutions due to their promotion of cognitive persistence. (2) Previous studies have suggested that the P200-600 component may reflect the formation of novel and rich associations, with higher P200-600 amplitudes observed in spontaneous insight solutions than in noninsight solutions [55]. Furthermore, research by Cui et al. [17] revealed that subliminal low rewards induced a greater number of insight solutions. MSM theory posits that insight solutions benefit from cognitive flexibility [69]. However, in the present study, no significant difference was found between the insight rates of real rewards and hypothetical rewards. The cause may be a bias in self-reports, although self-reports differentiating between insight and analytic solutions are reliable, and behavioral and neuroimaging markers have consistently provided evidence [16, 35, 38]. However, the choice of insight can be biased, as participants tend to misremember their analytic solutions as insights when they are informed that the problems they have solved are highly uncommon [25]. According to the theory of event coding, event files allow the selection of actions according to the effects they are likely to produce [31, 33]. Selecting a response can be considered a dynamic process of uncertainty reduction; it involves the intentional weighting of feature dimensions that are expected to be relevant for the task or that are suggested by the context [34]. We infer that the higher weighting given to real rewards may influence the choice of insight judgments, thereby facilitating a higher insight rate for real rewards. This could explain why no significant difference was observed between the insight rates of real rewards and hypothetical rewards.

Limitations and directions for future studies

There are several limitations to this study. Firstly, creativity is generally considered an active process involving both generation and evaluation. The CRA task primarily reflects a generation phase, combining remote association [11] based on the search for semantic memory and autobiographical memory [46, 50, 56]. Future experiments should focus on the evaluation process of creativity construction. Secondly, although the MSM theory suggests that flexibility bias involves less cognitive control than persistence, this study did not directly assess the level of cognitive control. Therefore, the findings can only illustrate the effect of reward on cognitive flexibility and persistence in creativity. Thirdly, a larger sample size would enhance the robustness and generalizability of the findings; thus, future studies should aim to include larger EEG samples. Furthermore, this study only examined the distinct impact of varying reward levels without including a control condition devoid of rewards. Future research should incorporate larger sample sizes and include control conditions without rewards to provide a comprehensive understanding of how rewards affect creative problem-solving processes.

Conclusion

In conclusion, this study offers both behavioral and neural evidence addressing the contentious effects of rewards on creative cognition. Our findings indicate a positive impact of real rewards on creative remote associations. Notably, compared with real rewards, hypothetical rewards elicited more P200-600 components. These results contribute new insights into the relationship between rewards and creative problem solving, highlighting the crucial role of persistence/flexibility in the formation of creativity.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used chatgpt 4.0 to improve the language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Author contribution

C.C. and Y.J designed this study. C.C., Y.Y., and Y.J performed the study. C.C. and Y.J analyzed the data. C.C. wrote the main manuscript text and prepared figures. All authors reviewed the manuscript.

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Availability of data and materials

The data and code used in the study are available upon direct request and can be shared or re-used with permission from the authors and a formal data sharing agreement. The dataset, along with the relevant code, will be made publicly accessible via the Open Science Framework (OSF:https://osf.io/qv4db) following the publication of our paper.

Declarations

Ethics approval and consent to participate

This research was approved by the Ethics Committee of the School of Psychology, Northeast Normal University. Before starting the experimental task, participants received information about the purpose of the study, the task, and its duration and gave their written informed consent.

Informed consent

Informed consent was obtained from each participant and the study protocol was approved by the ethics committees of the School of Psychology, Northeast Normal University.

Competing interests

The authors declare no competing interests.

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