



# Reward expectation modulates multiple stages of auditory conflict control

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## ABSTRACT

Although mounting evidence has shown that reward can improve conflict control in the visual domain, little is known about whether and how reward affects conflict processing in the auditory domain. In the present study, we adopted an auditory Stroop task in which the meaning of a sound word ('male' or 'female') could be either congruent or incongruent with the gender of the voice (male or female speaker), and the participants were asked to discriminate the gender of the voice (the phonetic task) or the meaning of the word (the semantic task). Importantly, an auditory cue signalling a potential reward or no-reward for the current trial was presented prior to the sound word. In both tasks, relative to the congruent sound word, response to the incongruent sound word was delayed, i.e., an auditory Stroop effect. However, this auditory Stroop effect was reduced following a reward cue relative to a no-reward cue. Event-related potentials (ERPs) showed a stronger contingent negativity variation (CNV, 1000–1500 ms) for the reward cue than for the no-reward cue. The conflict negativity N<sub>inc</sub> (300–400 ms) was more negative-going for the incongruent word than for the congruent word, but this effect was significantly reduced in the reward condition. However, the late positive complex (LPC) showed at most a weak reward modulation. These findings suggest that reward expectation improves auditory conflict control by modulating different stages of conflict processing: promoting better attentional preparation for the upcoming target (CNV), and facilitating conflict detection (N<sub>inc</sub>) on the presentation of the target.

## 1. Introduction

In dealing with a world full of uncertainties, it is crucial for humans to recruit the cognitive control system to concentrate on information that is relevant to the current goal while ignoring task-irrelevant information. One hallmark of cognitive control is to monitor the compatibility of input and solve the conflict between incompatible information (Botvinick et al., 2001). A growing body of evidence has shown that reward or reward expectation plays a critical role in motivating cognitive control and facilitating conflict resolution (Botvinick and Braver, 2015; Krebs et al., 2010; Krebs et al., 2011; Padmala and Pessoa, 2011; Pessoa, 2009; Soutschek et al., 2015). While most of this evidence is from studies in the visual domain, little is known about the generalizability of the reward effect across modalities.

In studies on conflict control, a Stroop (Stroop, 1935) or Stroop-like task in which a visual stimulus contains either compatible or incompatible information is often used, with the incompatible information inducing conflict and impairing performance (e.g., delaying

responses or causing response errors). Importantly, the conflict effect is found to be reduced when the behavioural response could result in a monetary reward, suggesting that the processes of conflict control can be facilitated or altered by reward anticipation (Kang et al., 2017; Kang et al., 2018; Krebs et al., 2013; Padmala and Pessoa, 2011; Soutschek et al., 2015).

According to the dual-mechanism control (DMC) framework, there are two strategies for the control system to work: proactive control and reactive control (Braver, 2012). Specifically, proactive control serves to maintain goal-relevant information actively and in a sustained manner such that the control system is prepared for the upcoming demanding events. By contrast, reactive control works in a just-in-time manner that the control is mobilized after the demanding events are detected (Braver, 2012). It has been suggested that reward expectation can enhance cognitive control via either proactive or reactive control processes (Beck et al., 2010; Boehler et al., 2014; Braver, 2012; Fröber and Dreisbach, 2016; Jimura et al., 2010; Langford et al., 2016; Schevernels et al., 2015).

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To recruit proactive control, a cue is often presented prior to the upcoming events, such that attentional preparation can be implemented in advance (e.g., Beck et al., 2010; Fröber and Dreisbach, 2016; Jimura et al., 2010; Schevernels et al., 2015). This proactive control is echoed by sustained neural activity in the interval between the cue and the imperative events, and the sustained neural activity has been shown to be enhanced by reward (Gruber et al., 2013; Jimura et al., 2010; van den Berg et al., 2014; Vuillier et al., 2015). One of the neural markers is the contingent negative variation (CNV), an event-related potential (ERP) component appearing around 1000 ms after the onset of the cue (Tecce, 1972; Walter et al., 1964). In a cued Stroop task in which a cue was followed by the classical Stroop word, van den Berg et al. (2014) found that the cue that signalled potential reward for the current trial elicited stronger CNV than the cue that did not signal reward. They also found that participants who showed enhanced CNV following the reward-predictive cue also showed reduced behavioural interference following the reward-predictive cue. These results suggest that reward expectation improves attentional preparation, which facilitates the following conflict control processes.

Other studies found that reward expectation enhances reactive control, such as facilitating response inhibition (Boehler et al., 2014; Schevernels et al., 2015). Schevernels et al. (2015) used EEG (electroencephalography) to investigate the transient modulation of reward on response inhibition in a stop-signal task. They found that reward increased the stop signal-locked N1, reflecting enhanced top-down attention. This increased N1 was accompanied by enhanced frontal P3 responses to the stop signal in successfully stopped trials. This P3 effect was suggested to reflect reactive inhibition in this task. The authors argued that both proactive and reactive control are involved in the rewarded stop-signal task (Schevernels et al., 2015).

Despite the mounting evidence of reward-modulated conflict processing in the visual domain (van den Berg et al., 2014; Padmala and Pessoa, 2011; see Botvinick and Braver, 2015 for a review), little is known about whether and how reward expectation modulates conflict processing in the auditory domain. To investigate this issue, we need to understand how the processes of auditory conflict control are examined in previous studies. Indeed, modified versions of the Stroop task in the auditory modality are often used for this purpose. For example, a sound word 'high' or 'low' could be presented in a high- or low-pitched voice, leading to different congruencies between the word meaning and the phonetic property. Using this task, researchers (Haupt et al., 2009; Oehrns et al., 2015) found that responses to the incongruent stimuli (e.g., the word 'high' with a low-pitched voice or the word 'low' with a high-pitched voice) were significantly slower than responses to the congruent stimuli (e.g., the word 'high' with a high-pitched voice or the word 'low' with a low-pitched voice). A similar congruency effect was observed when the meaning of the word is related to gender information (e.g., the sound word 'man' or 'girl') while the voice is from either a male or a female speaker (Green and Barber, 1981). These results mimic the classical Stroop effect in the visual domain. Moreover, in the visual Stroop paradigm, the congruency effect is observed both when the color of the word is task-relevant while the meaning of the word is task-irrelevant (i.e., the classic Stroop effect) and when the meaning of the word is task-relevant while the color of the word is task-irrelevant (i.e., the reverse Stroop effect). This reverse Stroop effect is also observed in the auditory domain in which the incongruent phonetic features of the sound word could delay the response to the meaning of the sound word (Christensen et al., 2011; Green and Barber, 1981). Compared with the classic Stroop effect, the reverse Stroop effect is less robust and its locus

LPC is affected by reward remains inconclusive in the visual domain (Krebs et al., 2013; van den Berg et al., 2014), the effect of reward expectation on LPC in the auditory domain is still to be revealed.

## 2. Experiment 1a

### 2.1. Participants

Twenty-three graduate or undergraduate students from universities in Beijing took part in the study. Data from two participants were incomplete because they did not finish the experiment, and data from another two participants were excluded from analysis due to the lack of enough correct trials (< 55%) for the ERP analysis. The remaining nineteen participants (11 male, 20–25 years old) were all right-handed, with normal or corrected-to-normal vision and self-reported normal hearing. All the participants gave written informed consent, and were paid for their time. This study was approved by the Ethics Committee of the School of Psychological and Cognitive Sciences, Peking University.

### 2.2. Stimuli

Each trial consisted of an auditory cue and an auditory target, which were presented via Etymotic ER-2 air earphones (Etymotic Research, Elk Grove Lillage, IL). The cue was either a sine-wave tone with a high frequency (600 Hz) or a sine-wave tone with a low frequency (200 Hz). The target was either a sound word “male” or “female” at a sampling rate of 44,100 Hz (16 bit). This target sound word was produced either by a male speaker or by a female speaker, rendering four types of targets: the sound word “male” with a male voice, the sound word “male” with a female voice, the sound word “female” with a male voice, and the sound word “female” with a female voice. With this manipulation, the gender of the voice was either congruent or incongruent with the meaning of the sound word. All of the auditory stimuli were delivered binaurally at an intensity level of about 60 dB. The durations of the cue and the target were both 450 ms.

### 2.3. Design

A modified version of the auditory Stroop task was adopted (Fig. 1). At the beginning of each trial, a white cross was presented at the center of a black computer screen as a visual fixation sign. After 500 ms, the auditory cue (a high tone or a low tone) was presented for 450 ms, while the visual fixation remained on the screen. For half of the participants, the high tone indicated a potential reward while the low tone indicated no reward in the current trial. For the other half of the participants, the association between reward expectation (reward vs. no-reward) and the cue (high tone vs. low tone) was reversed. The visual fixation was replaced by a blank screen at the offset of the auditory cue. After a varying interval of 1100–1600 ms, the auditory target was presented. The visual fixation was presented again at the onset of the auditory target, and remained on the screen until the offset of the auditory target (i.e., 450 ms). The inter-trial interval was randomly varied from 1000 to 1500 ms.

Participants were required to accomplish two tasks: a phonetic task and a semantic task, with the task order counterbalanced over participants. In the phonetic task, participants were asked to discriminate the gender of the voice (male vs. female), while ignoring the task-irrelevant meaning of the word. In the semantic task, participants were asked to discriminate the meaning of the word (“male” vs. “female”) irrespective of the gender of the voice. Discriminations were made by pressing the “F” key in the keyboard with the index finger of the left hand and the “J” key with the index finger of the right hand. The mappings between the two response keys (“F” vs. “J”) and two categories (male voice vs. female voice for the phonetic task, sound word “male” vs. sound word “female” for the semantic task) were counterbalanced across participants. Thus, the experiment had a 2 (task type: phonetic task vs. semantic task) × 2 (reward expectation: reward vs. no-reward) × 2 (congruency: congruent vs. incongruent) within-participant design.

There were 48 trials in each of the 8 experimental conditions, resulting in 384 trials in total. The 384 trials were divided into 8 blocks of equal length (48 trials in each block), with 4 consecutive blocks of the phonetic task followed by 4 consecutive blocks of the semantic task, or vice versa. The four trial types (reward expectation × congruency) were equally distributed in each block and were presented in a pseud-randomized order, with the restriction that no more than three consecutive trials were from the same condition.

Prior to the formal experiment, participants were required to go through 24 practice trials for each of the two tasks. The procedure of practice trials was the same as the formal experimental trial, except that no reward information was given. For each participant, the baseline reaction time was obtained by calculating the mean reaction times (RT) of the practice trials with correct responses for the phonetic task and the semantic task, respectively. Participants were asked to respond as quickly and correctly as possible, and were explicitly informed, after the practice blocks, that reward could be given only when the response was both correct and faster than the baseline response in the reward condition. The accumulated total coins thus far were presented on the screen at the end of each block. Coins were exchanged for cash after the

incongruent condition, 94.0% (SD = 7.31) in the no-reward-congruent condition, 88.3% (SD = 9.55) in the no-reward-incongruent condition. For the semantic task, the proportion of remaining trials that included for statistical analyses were 92.3% (SD = 6.25) of all the trials in the reward-congruent condition, 88.9% (SD = 8.42) in the reward-incongruent condition, 92.1% (SD = 8.35) in the no-reward-congruent condition, 88.7% (SD = 9.78) in the no-reward-incongruent condition.

## 2.5. ERP a a

Cue-locked ERP and target-locked ERP analyses were conducted separately.

For cue-locked ERPs, we focused on the CNV, which has been suggested as an important signature of task preparation. Based on visual inspection of the potential reward effect and previous findings concerning CNV (Vuillier et al., 2015; van den Berg et al., 2014; Fan et al., 2007; Schevernels et al., 2015), we obtained the cue-related CNV from the time range of 1000–1500 ms post-cue onset, for each of the 15 electrode sites from anterior to posterior areas (Fz, F3, F4, FCz, FC3, FC4, Cz, C3, C4, CPz, CP3, CP4, Pz, P3, P4), respectively. To examine the topographical distribution of the cue-related CNV, the 15 electrodes were grouped into 5 clusters: frontal cluster (Fz, F3, F4), frontocentral cluster (FCz, FC3, FC4), central cluster (Cz, C3, C4), parietocentral cluster (CPz, CP3, CP4) and parietal cluster (Pz, P3, P4). Given that the cue was uninformative with regard to the type of the upcoming target, trials were collapsed over task type and target congruency. A two-way repeated-measures ANOVA was thus conducted on the mean amplitudes of CNV, with reward expectation (reward vs. no-reward) and electrode cluster (frontal, frontocentral, central, parietocentral, and parietal) as within-participant factors.

For the target-locked ERP analysis, we focused on the  $N_{inc}$  component (300–400 ms after target onset). Based on visual inspection of the potential conflict effect and previous findings concerning  $N_{inc}$  (Buzzell et al., 2013; Donohue et al., 2012; Coderre et al., 2011; Chen et al., 2011; Donohue et al., 2016), we selected 15 electrode sites from anterior to posterior areas (Fz, F3, F4, FCz, FC3, FC4, Cz, C3, C4, CPz, CP3, CP4, Pz, P3, P4), and grouped them into five clusters (frontal: Fz, F3, F4; frontocentral: FCz, FC3, FC4; central: Cz, C3, C4; parietocentral: CPz, CP3, CP4; parietal: Pz, P3, P4). For  $N_{inc}$ , mean amplitudes over the 300–400 ms time window for each condition were analyzed by repeated-measures ANOVA with four within-participant factors: task type (phonetic task vs. semantic task), reward expectation (reward vs. no-reward), congruency (congruent vs. incongruent), and electrode cluster (frontal, frontocentral, central, parietocentral, parietal).

Moreover, based on visual inspection and previous findings concerning the late positive complex (LPC) (Chen et al., 2011; Buzzell et al., 2013; Donohue et al., 2016; Donohue et al., 2012; Liotti et al., 2000; West et al., 2010), we examined LPC in the time range of 600–800 ms post-stimulus onset, for each of the 15 electrode sites from anterior to posterior areas (Fz, F3, F4, FCz, FC3, FC4, Cz, C3, C4, CPz, CP3, CP4, Pz, P3, P4), respectively. A repeated-measures ANOVA was conducted on the mean LPC amplitudes with four within-participant factors: task type (phonetic task vs. semantic task), reward expectation (reward vs. no-reward), congruency (congruent vs. incongruent), and electrode cluster (frontal, frontocentral, central, parietocentral, parietal).

## 3. R

### 3.1. B a a

#### 3.1.1. E a

For each participant, error rates were obtained by calculating the proportion of incorrect and omission trials (Table 1). A 2 (phonetic task vs. semantic task)  $\times$  2 (reward vs. no-reward)  $\times$  2 (congruent vs. incongruent) repeated-measures ANOVA on error rates showed a main

effect of congruency,  $F(1, 18) = 21.778$ ,  $p < .001$ ,  $\eta^2 = 0.547$ , with higher error rates for the incongruent than for the congruent conditions (2.0% vs. 5.5%). No other main effect or interaction reached significance.

#### 3.1.2. R ac

For the analyses of reaction times (RTs), trials with incorrect responses were firstly excluded. Trials with RTs more than three standard deviations above or below the mean in each experimental condition were also excluded (0.9%). A three-way repeated-measures ANOVA was conducted on RTs, with task type (phonetic task vs. semantic task), reward expectation (reward vs. no-reward), and congruency (congruent vs. incongruent) as within-participant factors. Results showed a main effect of reward expectation,  $F(1, 18) = 8.014$ ,  $p = .011$ ,  $\eta^2 = 0.308$ , with shorter RTs for the reward than for the no-reward conditions (498 vs. 532 ms). The main effect of congruency was significant,  $F(1, 18) = 74.940$ ,  $p < .001$ ,  $\eta^2 = 0.806$ , with shorter RTs for the congruent than for the incongruent conditions (494 vs. 535 ms). The interaction between task type and congruency and the interaction between reward expectation and congruency were significant,  $F(1, 18) = 10.433$ ,  $p = .005$ ,  $\eta^2 = 0.367$ , and  $F(1, 18) = 5.735$ ,  $p = .028$ ,  $\eta^2 = 0.242$ , respectively. No other main effect or interaction reached significance ( $p > .4$ ).

To explore the interaction between task type and congruency, we conducted paired  $t$ -tests, collapsing the data over reward conditions. RTs were shorter for the congruent than for the incongruent condition in both the phonetic task (486 vs. 539 ms,  $t(18) = 7.455$ ,  $p < .001$ ) and the semantic task (503 vs. 532 ms,  $t(18) = 6.368$ ,  $p < .001$ ). Nevertheless, the congruency or conflict effect (i.e., RT in the incongruent condition - RT in the congruent condition) was larger in the phonetic task than in the semantic task (53 vs. 29 ms,  $t(18) = 3.254$ ,  $p = .004$ ), confirming the significant interaction reported above.

To explore the interaction between reward and congruency, we conducted paired  $t$ -tests, collapsing the data over task types. RTs were shorter in the congruent condition than in the incongruent condition for both reward trials (480 vs. 515 ms,  $t(18) = 7.883$ ,  $p < .001$ ) and no-reward trials (509 vs. 556 ms,  $t(18) = 7.477$ ,  $p < .001$ ). Nevertheless, the congruency (conflict) effect was smaller in the reward condition than in the no-reward condition (35 vs. 47 ms,  $t(18) = 2.369$ ,  $p = .029$ ), indicating that reward reduced the behavioural conflict effect.

To examine whether the smaller congruency effect in the reward condition than in the no-reward condition was simply a by-product of the faster response speed in the former, we calculated the proportion of the congruency effect in experimental conditions ( $[\text{incongruent RT} - \text{congruent RT}] / \text{congruent RT}$ ) (Chen et al., 2011). A 2 (phonetic vs. semantic task)  $\times$  2 (reward vs. no-reward) ANOVA on the proportion of the congruency effect showed a main effect of task type,  $F(1, 18) = 14.411$ ,  $p < .001$ ,  $\eta^2 = 0.445$ , suggesting that the congruency effect was indeed larger in the phonetic task than in the semantic task (10.7% vs. 5.8%). The main effect of reward expectation was marginally significant,  $F(1, 18) = 4.076$ ,  $p = .059$ ,  $\eta^2 = 0.185$ , indicating that the congruency effect was smaller in the reward condition than in the no-reward condition (7.2% vs. 9.3%). These results confirmed that the observed reward modulation on the conflict effects cannot be simply reduced to the general speed-up of behavioural responses.

## 3.2. ERP

### 3.2.1. C a : CNV (1000–1500 )

ANOVA on CNV amplitudes (Table 2 and Fig. 2) showed a main effect of reward expectation,  $F(1, 18) = 4.959$ ,  $p = .039$ ,  $\eta^2 = 0.216$ , with a larger CNV amplitude in the reward condition than in the no-reward condition ( $-1.79$  vs.  $-1.18 \mu\text{V}$ ). No other main effect or interaction reached significance.

**Tab 1**  
Mean RT (ms) and error rate (%) with standard deviation (SD) in each experimental condition.

	Phonetic task				Semantic task			
	Reward		No-reward		Reward		No-reward	
	Con	Incon	Con	Incon	Con	Incon	Con	Incon
RT (ms)	474 (81)	519 (100)	498 (74)	559 (96)	487 (59)	511 (65)	519 (76)	553 (82)
Error rate (%)	1.8 (3.4)	6.6 (6.1)	2.8 (4.1)	6.7 (7.6)	1.4 (1.6)	4.5 (3.0)	2.0 (3.4)	4.0 (4.5)

Note: congruent, Con; incongruent, Incon.

### 3.2.2. *Ta a : c flc - a N c (300–400)*

ANOVA on  $N_{inc}$  amplitudes (Table 3 and Fig. 3, left panel of Fig. 4) showed a main effect of task type,  $F(1, 18) = 11.275$ ,  $p = .004$ ,  $\eta^2 = 0.384$ , with a more negative-going  $N_{inc}$  amplitude in the semantic task than in the phonetic task (0.63 vs. 1.51  $\mu V$ ). The main effect of reward expectation was significant,  $F(1, 18) = 9.759$ ,  $p = .006$ ,  $\eta^2 = 0.352$ , with a more negative-going  $N_{inc}$  in the no-reward condition than in the reward condition (0.66 vs. 1.49  $\mu V$ ). The main effect of congruency was significant,  $F(1, 18) = 18.544$ ,  $p < .001$ ,  $\eta^2 = 0.507$ , with a more negative-going  $N_{inc}$  in the incongruent condition than in the congruent condition (0.51 vs. 1.63  $\mu V$ ). The main effect of electrode cluster was significant,  $F(1, 72) = 46.462$ ,  $p < .001$ ,  $\eta^2 = 0.721$ . The interaction between reward expectation and congruency,  $F(1, 18) = 4.944$ ,  $p = .039$ ,  $\eta^2 = 0.215$ , task type and congruency,  $F(1, 18) = 4.931$ ,  $p = .039$ ,  $\eta^2 = 0.215$ , task type and electrode cluster,  $F(4, 72) = 8.996$ ,  $p < .001$ ,  $\eta^2 = 0.333$ , congruency and electrode cluster,  $F(4, 72) = 6.197$ ,  $p < .001$ ,  $\eta^2 = 0.256$ , were all significant. No other interaction reached significance.

To explore the interaction between reward expectation and congruency, we conducted paired  $t$ -tests, collapsing the data over task types and electrode clusters. Results showed that the  $N_{inc}$  amplitude was more negative-going in the incongruent condition than the congruent for the no-reward trials (−0.16 vs. 1.47  $\mu V$ ,  $(18) = 4.720$ ,  $p < .001$ ), but for the reward trials (1.17 vs. 1.80  $\mu V$ ,  $p > .08$ ). The  $N_{inc}$  conflict (congruency) effect was calculated by subtracting the mean  $N_{inc}$  amplitude in the congruent condition from the mean  $N_{inc}$  amplitude in the incongruent condition. Paired  $t$ -tests showed a larger  $N_{inc}$  conflict effect in the no-reward condition than in the reward condition (−1.62 vs. −0.63  $\mu V$ ,  $(18) = 2.223$ ,  $p = .039$ ), suggesting that reward expectation reduced the  $N_{inc}$  conflict (or congruency) effect.

To explore the interaction between task type and congruency, we conducted paired  $t$ -test, collapsing the data over reward conditions and electrode clusters. Results showed that the  $N_{inc}$  amplitude was more negative-going in the incongruent condition than in the congruent condition for the phonetic task (0.73 vs. 2.29  $\mu V$ ,  $(18) = 4.810$ ,  $p < .001$ ), and for the semantic task (0.29 vs. 0.98  $\mu V$ ,  $(18) = 2.097$ ,  $p = .050$ ). Nevertheless, the  $N_{inc}$  conflict effect was larger in the phonetic task than in the semantic task (−1.56 vs. −0.69  $\mu V$ ,  $(18) = 2.221$ ,  $p = .039$ ).

To explore the interaction between congruency and electrode cluster, we conducted paired  $t$ -tests, collapsing the data over reward conditions and task types. Results showed that the  $N_{inc}$  amplitude was more negative-going in the incongruent condition than in the congruent condition over all the electrode clusters (frontal: −1.18 vs. 0.07  $\mu V$ ,  $(18) = 3.892$ ,  $p = .001$ ; frontocentral: −0.84 vs. 0.60  $\mu V$ ,  $(18) = 4.261$ ,  $p < .001$ ; central: 0.06 vs. 1.38  $\mu V$ ,  $(18) = 4.378$ ,

$p < .001$ ; parietocentral: 1.67 vs. 2.63  $\mu V$ ,  $(18) = 3.968$ ,  $p = .001$ ; parietal: 2.79 vs. 3.50  $\mu V$ ,  $(18) = 3.614$ ,  $p = .002$ ). Nevertheless, one-way ANOVA on the  $N_{inc}$  conflict effect showed a main effect of electrode cluster,  $F(4, 72) = 6.196$ ,  $p < .001$ ,  $\eta^2 = 0.256$ . Pairwise comparisons with Bonferroni correction showed larger  $N_{inc}$  conflict effects over frontocentral and central clusters than over parietocentral cluster (−1.44, −1.32 vs. −0.96  $\mu V$ ).

### 3.2.3. *Ta a : LPC (600–800)*

ANOVA on LPC amplitudes (Table 3 and Fig. 3, right panel of Fig. 4) showed a main effect of reward expectation,  $F(1, 18) = 4.770$ ,  $p = .042$ ,  $\eta^2 = 0.209$ , and a main effect of electrode cluster,  $F(4, 72) = 19.552$ ,  $p < .001$ ,  $\eta^2 = 0.521$ . The main effect of task type and the main effect congruency, however, did not reach significance,  $F(1, 18) = 2.563$ ,  $p > .1$ , and  $F(1, 18) = 1.221$ ,  $p > .2$ . The interaction between task type and congruency,  $F(1, 18) = 4.821$ ,  $p = .041$ ,  $\eta^2 = 0.211$ , between task type and electrode cluster,  $F(4, 72) = 6.600$ ,  $p < .001$ ,  $\eta^2 = 0.268$ , and between congruency and electrode cluster,  $F(4, 72) = 5.645$ ,  $p < .001$ ,  $\eta^2 = 0.239$  were significant. Moreover, the three-way interaction between task type, congruency, and electrode cluster reached significance,  $F(4, 72) = 3.093$ ,  $p = .021$ ,  $\eta^2 = 0.147$ , so the three-way interaction between task type, reward expectation, and congruency,  $F(1, 18) = 5.410$ ,  $p = .032$ ,  $\eta^2 = 0.231$ . No other main effect or interaction was significant.

Separate analyses were conducted for the phonetic task and semantic task. For the phonetic task, 2 (reward expectation)  $\times$  2 (congruency)  $\times$  5 (electrode cluster) ANOVA showed an interaction between congruency and electrode cluster,  $F(4, 72) = 7.195$ ,  $p < .001$ ,  $\eta^2 = 0.286$ , and a main effect of electrode cluster,  $F(4, 72) = 19.471$ ,  $p < .001$ ,  $\eta^2 = 0.520$ . No other effect was significant. To explore the interaction, LPC amplitudes were collapsed over reward conditions as reward did not interact with any other factors. Paired  $t$ -test showed that LPC amplitudes were more positive in the incongruent condition than in the congruent condition over the parietal region (3.275 vs. 2.546  $\mu V$ ;  $(18) = 2.671$ ,  $p = .016$ ). For the semantic task, ANOVA showed that the interaction between reward expectation and congruency was marginally significant,  $F(1, 18) = 4.016$ ,  $p = .06$ ,  $\eta^2 = 0.182$ . To explore the interaction, LPC amplitudes were collapsed over electrode clusters. Paired  $t$ -tests showed that LPC amplitudes were more positive in the incongruent condition than in the congruent condition for the reward trials (2.80 vs. 1.64  $\mu V$ ,  $(18) = 3.100$ ,  $p = .006$ ), but for the no-reward trials (1.14 vs. 1.07  $\mu V$ ,  $(18) = 0.181$ ,  $p = .859$ ).

## 4. Discussion

The main goal of the present study is to investigate whether and

**Tab 2**  
Mean amplitude ( $\mu V$ ) of CNV with SD for reward and no-reward conditions, and five electrode clusters during the cue phase.

	Frontal	Frontocentral	Central	Parietocentral	Parietal
CNV (1000–1500)					
No-reward	−1.12 (2.29)	−1.18 (2.20)	−0.98 (1.64)	−1.08 (1.54)	−1.52 (1.81)
Reward	−1.69 (3.06)	−1.79 (2.89)	−1.75 (2.42)	−1.80 (1.91)	−1.89 (1.98)

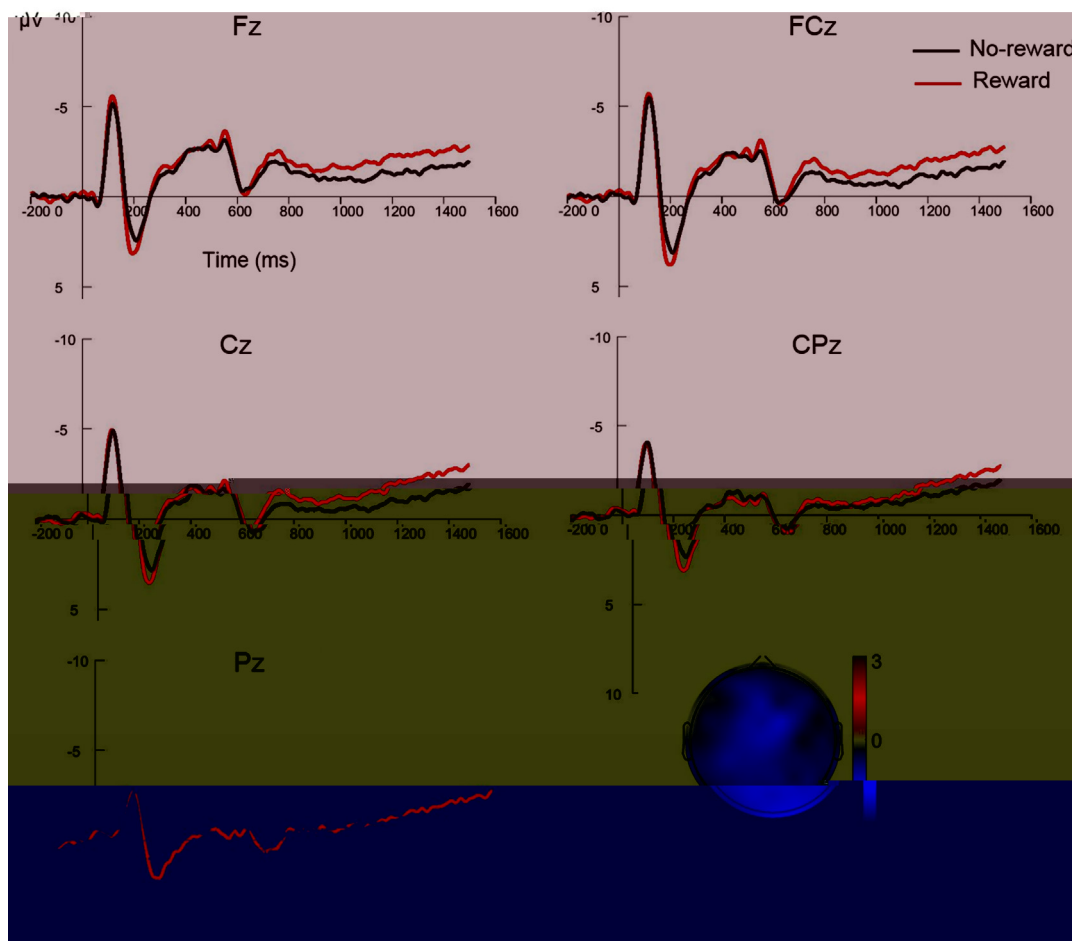


Fig. 2. ERP responses locked to the cue onset in the reward condition (red) and no-reward condition (black) at Fz, FCz, Cz, CPz and Pz electrode sites. B: topography of the average of the CNV reward effect. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

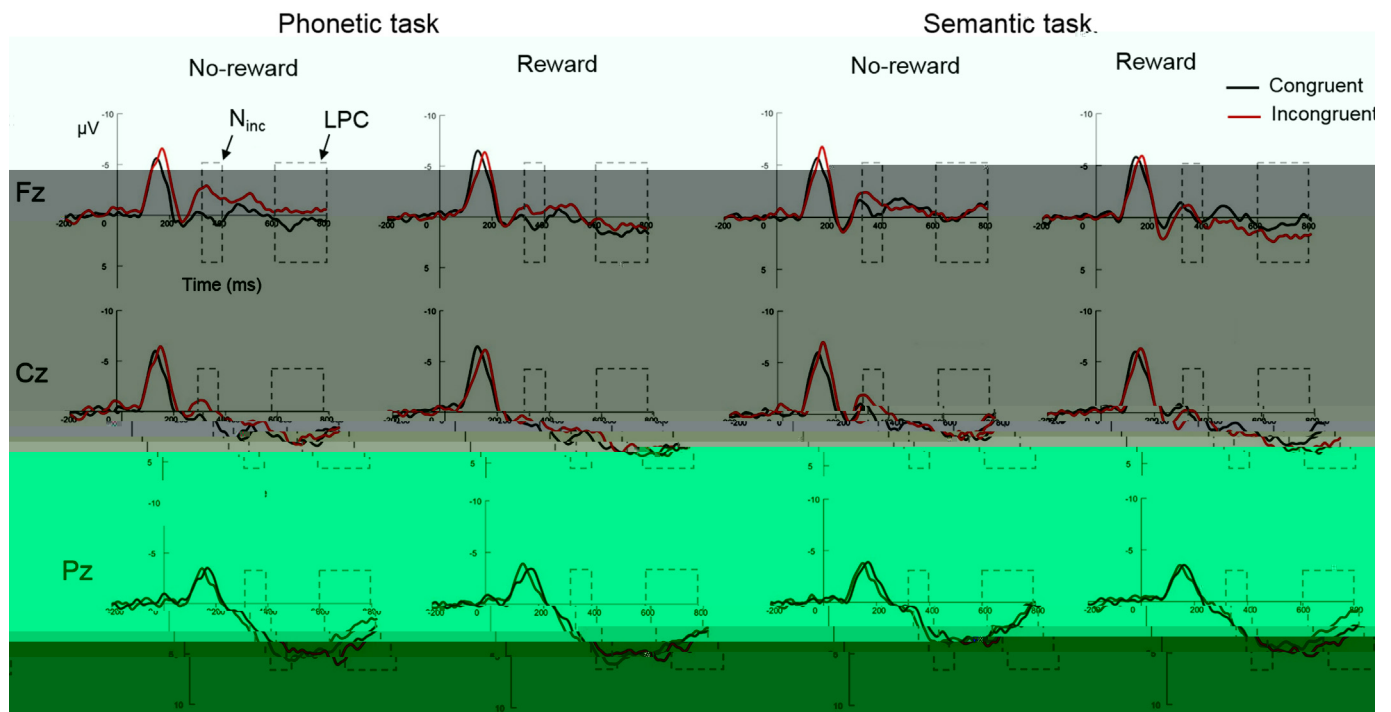
Table 3  
Mean amplitude (µV) of  $N_{inc}$  and LPC with SD for each experimental condition and each electrode cluster during the target phase.

	Phonetic task				Semantic task			
	Reward		No-reward		Reward		No-reward	
	Con	Incon	Con	Incon	Con	Incon	Con	Incon
$N_c$ (300–400)								
Frontal	0.71 (3.83)	-0.70 (3.21)	0.22 (2.25)	-2.05 (3.76)	-0.24 (2.89)	-0.25 (3.73)	-0.43 (2.50)	-1.51 (3.10)
Frontocentral	1.44 (4.07)	0.03 (3.39)	0.87 (2.69)	-1.61 (4.03)	0.23 (3.03)	-0.17 (4.36)	-0.14 (3.10)	-1.61 (3.66)
Central	2.29 (4.01)	1.08 (3.31)	1.84 (3.16)	-0.36 (3.67)	0.82 (3.06)	0.47 (3.92)	0.55 (3.13)	-0.96 (3.36)
Parietocentral	3.69 (3.65)	2.81 (3.04)	3.22 (2.99)	1.47 (3.28)	1.88 (2.88)	1.86 (3.16)	1.72 (2.89)	0.52 (2.97)
Parietal	4.40 (3.13)	3.83 (2.36)	4.23 (2.62)	2.83 (2.57)	2.79 (2.77)	2.77 (2.31)	2.58 (2.37)	1.74 (2.36)
LPC (600–800)								
Frontal	1.38 (2.97)	0.55 (4.14)	0.31 (2.36)	-0.30 (3.65)	0.59 (3.06)	1.91 (3.18)	-0.06 (2.27)	-0.07 (2.49)
Frontocentral	2.54 (3.06)	1.94 (3.95)	1.42 (2.43)	0.79 (4.03)	1.56 (2.78)	2.54 (3.43)	0.83 (2.49)	0.62 (3.03)
Central	3.32 (2.95)	2.96 (3.42)	2.25 (2.49)	2.06 (4.04)	2.11 (2.60)	3.10 (3.33)	1.40 (2.55)	1.27 (3.14)
Parietocentral	3.69 (2.67)	3.87 (2.99)	2.75 (2.49)	3.12 (3.70)	2.27 (2.34)	3.55 (2.74)	1.73 (2.35)	2.02 (3.04)
Parietal	2.76 (2.72)	3.33 (2.77)	2.33 (2.40)	3.22 (3.26)	1.67 (2.34)	2.93 (1.95)	1.43 (2.07)	1.86 (2.59)

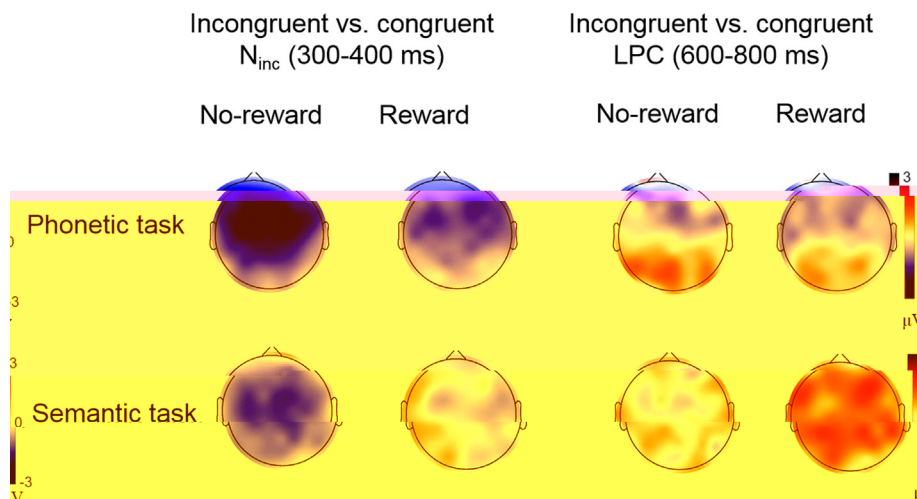
how reward expectation modulates the temporal profile of auditory conflict processing: the attentional preparation, the conflict detection and resolution. By adopting an auditory Stroop task, we demonstrated that, behaviourally, in both the phonetic task (relating to the classical Stroop effect in the auditory domain) and the semantic task (relating to the reverse Stroop effect), responses were delayed when the meaning of the sound word was incongruent with the gender of the voice. Moreover, the current auditory Stroop tasks replicated the finding in

the visual domain that the classical Stroop effect is often larger in magnitude than the reverse Stroop effect (MacLeod, 1991).

Importantly, by presenting a cue that signalled potential reward or no reward prior to the target word, we found that the auditory Stroop effect was reduced following the reward cue as compared with following the no-reward cue, suggesting that reward expectation improves the resolution of auditory information conflict. Adding to the literature that showed reward-facilitated conflict resolution in the visual domain



**F . 3.** ERP responses locked to the stimulus onset of each experimental condition in the phonetic task (left) and semantic task (right) at Fz, Cz, Pz electrode sites. The time ranges of  $N_{inc}$  and LPC are highlighted. The  $N_{inc}$  conflict effect (incongruent vs. congruent) decreased in the reward condition as compared with no-reward condition in both tasks. For the LPC conflict effect, reward modulation appeared for the semantic task, but not the phonetic task.



**F . 4.** Topographical maps of  $N_{inc}$  (300–400 ms) and LPC (600–800 ms) difference waves (incongruent vs. congruent).

(van den Berg et al., 2014; Padmala and Pessoa, 2011; Soutschek et al., 2015) and in cross-modal contexts (e.g., Kang et al., 2017; Kang et al., 2018), our results provide important new evidence suggesting a general role of reward in motivating cognitive control regardless of the sensory context (Anderson, 2016).

With EEG recording, we found that the ERP components related to different stages of conflict control are selectively modulated by reward expectation. During the stage of attentional preparation, relative to the no-reward cue, the reward cue evoked stronger frontocentral CNV about 1000 ms after the onset of the cue, suggesting an improved preparatory state for the upcoming target when reward is expected. As a neural signature of task preparation (Tecce, 1972; Walter et al., 1964), CNV has been found to be related to the neural activity in the frontoparietal attentional control network (Fan et al., 2007; Grent't-Jong and Woldorff, 2007; Hillyard, 1969). It is enhanced by reward in a broad

range of tasks such as visual Stroop (Krebs et al., 2013; van den Berg et al., 2014), Go-Nogo (Vuillier et al., 2015), and rapid signal detection (Hughes et al., 2013). The converging evidence suggests that CNV, as an important component of the control hub (Miller, 2000; Zanto and Gazzaley, 2013), can be flexibly recruited or modulated to realize the current goal.

For conflict processing upon the target, while previous studies in the visual domain have documented important ERP components for conflict detection and resolution: N2, N450 and sustained posterior positivity, less is known for the auditory domain. Here we suggest that  $N_{inc}$  is involved in early auditory conflict detection whereas LPC is involved in late conflict resolution.  $N_{inc}$ , a N2-like component, shows a strong conflict-related effect and is distributed over the frontocentral areas, pointing to conflict control in the prefrontal cortex (Botvinick et al., 2001; Folstein and Van Petten, 2008; Gratton et al., 2018; Miller, 2000;

West et al., 2004). The auditory conflict-related  $N_{inc}$  is associated with conflict detection, which is in the same vein as detecting a “mismatch” (Buzzell et al., 2013; Donohue et al., 2012). In the present study, the  $N_{inc}$  conflict or congruency effect was larger in the phonetic task than in the semantic task, closely mirroring the pattern of the behavioural conflict effect. More importantly, regardless of the task type, the  $N_{inc}$  conflict effect was consistently reduced in the reward condition than in the no-reward condition, reflecting a reward modulation on conflict detection.

While the reduced  $N_{inc}$  conflict effect by reward expectation in the present study is consistent with a previous study in the visual domain showing that the  $N_{inc}$  conflict effect is reduced when attention is better prepared for the upcoming Stroop target (Appelbaum et al., 2012), it is at odds with the null effect in van den Berg et al. (2014) in which no reduction of  $N_{inc}$  conflict effect was observed when reward was expected. It should be noted that behaviourally van den Berg et al. (2014) did not observe a modulation of reward on the congruency (conflict) effect either. Taken together, these results demonstrate a close dependency between the  $N_{inc}$  and the behavioural conflict effect, regardless of sensory modality.

In contrast to the consistent  $N_{inc}$  conflict effect that was reduced by reward expectation in both the phonetic and semantic tasks, the pattern of reward modulation on LPC effect varied according to particular tasks. In the phonetic task, LPC was generally more positive in the incongruent condition than in the congruent condition over the parietal area irrespective of reward expectation. Both the time range and scalp distribution of the observed LPC effect are similar to the pattern shown in the visual Stroop task (e.g., SP in Larson et al., 2009; Liotti et al., 2000; West, 2003). The absence of a reward effect on LPC conflict in this task is consistent with a recent study using the classical visual Stroop task (van den Berg et al., 2014).

By contrast, in the semantic task in which the reverse auditory Stroop effect was observed, there was no difference in LPC between the congruent and incongruent trials in the no-reward conditions. But the difference did appear in the reward conditions, and this reward-contingent LPC effect was not specific to the parietal cluster. We speculate that when the task-relevant dimension (semantics) is of higher automatic response tendency as compared with the task-irrelevant dimension (the gender of the voice), less response competition would occur in general. As reward would increase the automatic response tendency (Wang et al., 2018), responses to the congruent stimuli would become even faster in the congruent condition, leading to less positive-going LPC responses and a larger LPC conflict effect. Obviously, more studies are needed to verify this modulation of reward on the LPC conflict effect.

One might notice that the time range of LPC observed here was later than the behavioural response latency (i.e., the mean RT). Similar results were observed in a previous study (Chen et al., 2011) in which the parietal conflict LPC/SP was in the time range of 600–1000 ms and the response-specific effect shown in SP was in the time range of 1000–1200 ms, even though the longest mean RT across experimental conditions was 965 ms. One possible explanation for this phenomenon is that the effect on LPC might be driven mainly by the slowest trials where the congruency effect is the greatest (Chen et al., 2011). To test this account, we divided the trials into slow and fast RT bins in reference to the 50th percentile of RTs in each condition and examined how the congruency effect differed in different RT bins. The results showed a larger congruency/conflict effect for the slow RT bin (53 ms) as compared with the fast RT bin (28 ms),  $t(18) = 5.039$ ,  $p < .001$ , also pointing to the possibility that LPC/SP is sensitive to response competition, as a strong response competition leads to a slow response.

Although our findings suggest a possible role of LPC in conflict processing, it should be noted that there is still no general agreement on this point. Some studies suggested that more positive LPC in incongruent trials than congruent trials signals increased implementation of attentional control (Coderre et al., 2011; Donohue et al., 2016; Larson

et al., 2009). For example, Larson et al. (2009) found that LPC/SP showed stronger responses in the incongruent condition than in the congruent condition, and this effect was larger following a congruent trial than following an incongruent trial. However, other studies suggested that the LPC/SP is related to general response selection rather than specific conflict resolution, as the SP amplitude can be positively correlated with RT and accuracy (West et al., 2005). The role of LPC/SP on conflict processing needs further research.

Our results also suggested that different neural components are related to the proactive control and reactive control, as proposed by the dual mechanisms of cognitive control (DMC; Braver, 2012). The CNV can be taken as the neural signature of proactive control because it is engaged in anticipating the upcoming control need (Vuillier et al., 2015; van den Berg et al., 2014; Fan et al., 2007; Schevernels et al., 2015). The  $N_{inc}$  can be taken as the neural signature of reactive control, because it signals the current need for control which could not be predicted in advance (Kang et al., 2018; van den Berg et al., 2014). As an extension, our results further showed that these different components can be modulated by reward, suggesting a general role of reward in motivating cognitive control regardless of the dominant control mode.

## 5. C

The present study demonstrates that reward expectation improves conflict control by modulating multiple stages of conflict processing. Relative to a no-reward context, reward context promotes attentional preparation for the upcoming target (CNV) and facilitates the detection of conflict ( $N_{inc}$ ), which in turn leads to a smaller behavioural conflict effect. Together with evidence from visual and audiovisual domains, our findings not only suggest a general role of reward in motivating cognitive control, but also help to understand the temporal dynamics of the control processes.

## A

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