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doi: 10.1093/cercor/bhy275
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ORIGINAL ARTICLE

Neural Dynamics of Reward-Induced Response Activation and Inhibition

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Abstract

Reward-predictive stimuli can increase an automatic response tendency, which needs to be counteracted by effortful response inhibition when this tendency is inappropriate for the current task. Here we investigated how the human brain implements this dynamic process by adopting a reward-modulated Simon task while acquiring EEG and fMRI data in separate sessions. In the Simon task, a lateral target stimulus triggers an automatic response tendency of the spatially corresponding hand, which needs to be overcome if the activated hand is opposite to what the task requires, thereby delaying the response. We associated high or low reward with different targets, the location of which could be congruent or incongruent with the correct response hand. High-reward targets elicited larger Simon effects than low-reward targets, suggesting an increase in the automatic response tendency induced by the stimulus location. This tendency was accompanied by modulations of the lateralized readiness potential over the motor cortex, and was inhibited soon after if the high-reward targets were incongruent with the correct response hand. Moreover, this process was accompanied by enhanced theta oscillations in medial frontal cortex and enhanced activity in a frontobasal ganglia network. With dynamical causal modeling, we further demonstrated that the connection from presupplementary motor area (pre-SMA) to right inferior frontal cortex (rIFC) played a crucial role in modulating the reward-modulated response inhibition. Our results support a dynamic neural model of reward-induced response activation and inhibition, and shed light on the neural communication between reward and cognitive control in generating adaptive behaviors.

Key words: LRP, MFC, response control, reward, theta-band oscillation

Introduction

It is crucial for humans to coordinate between automatic (i.e., bottom-up) and goal-directed (i.e., top-down) behavioral tendencies. A growing body of studies has shown that both the bottom-up and the top-down cognitive processing can be modulated by reward (Awh et al. 2012; Yee and Braver 2018), the driving force of human behavior (Berridge and Robinson 1998). On the one hand, stimuli that are associated with reward attract visual attention (Theeuwes and Belopolsky 2012; Wang et al. 2013) and provoke motor reactions (Bundt et al. 2016). On the other hand, reward expectation improves task performance by motivating the inhibition of task-irrelevant information (Padmala and Pessoa 2011; Kang et al. 2017). Although the bias for reward can be beneficial in an evolutionary sense, it nevertheless causes undesirable behavioral consequences when it is in conflict with the current goals (Dayan et al. 2006). Thus, top-down cognitive control needs to overcome such prepotencies to realize task goals and ensure healthy functioning (Hare et al. 2011; Boehler et al. 2012). Despite the increasing number of studies that focus either on the reward-modulated cognitive bias or on the reward-modulated inhibitory control, it remains inhibition by tuning the frontosubthalamic pathway. For example, Herz et al. (2014)

Therefore, all the experiments had a 2 (reward: high vs. low) × 2 (spatial congruency: congruent vs. incongruent) design, rendering to 4 experimental conditions: high-reward congruent (HC), high-reward incongruent (HIC), low-reward congruent (LC), and low-reward incongruent (LIC). Given that the mapping between the response button and response hand was fixed (left index finger for “E” and right index finger for “P”), while the mapping between reward association and response hand was counterbalanced across participants such that high-reward was associated with the left hand and low-reward was associated with the right hand for half of the participants whereas the

Event-Related Potential Analysis

For event-related potential (ERP) analysis, we focused on both the stimulus-locked LRP, which is time-locked to the onset of the stimulus, and the response-locked LRP, which is time-locked to the onset of the response (Töllner et al. 2012) to show the reward-induced response activation. In each trial, stimulus-locked epochs were extracted from the interval of −200 to 800 ms relative to stimulus onset, while response-locked epochs were derived from the interval of −1000 to 200 ms relative to response onset. Note here that none of the response-locked epochs had overlap with the epoch of the previous trial or the next trial, because all of the RTs (after the being modeled as separate regressors. The 4 event types were time-locked to the stimulus onset, and modeled by an impulse function convolved with a canonical synthetic hemodynamic response function and its time derivatives (Friston et al. 1998; Hopfinger et al. 2000

The hypothesis tested by our DCM analysis was which path-

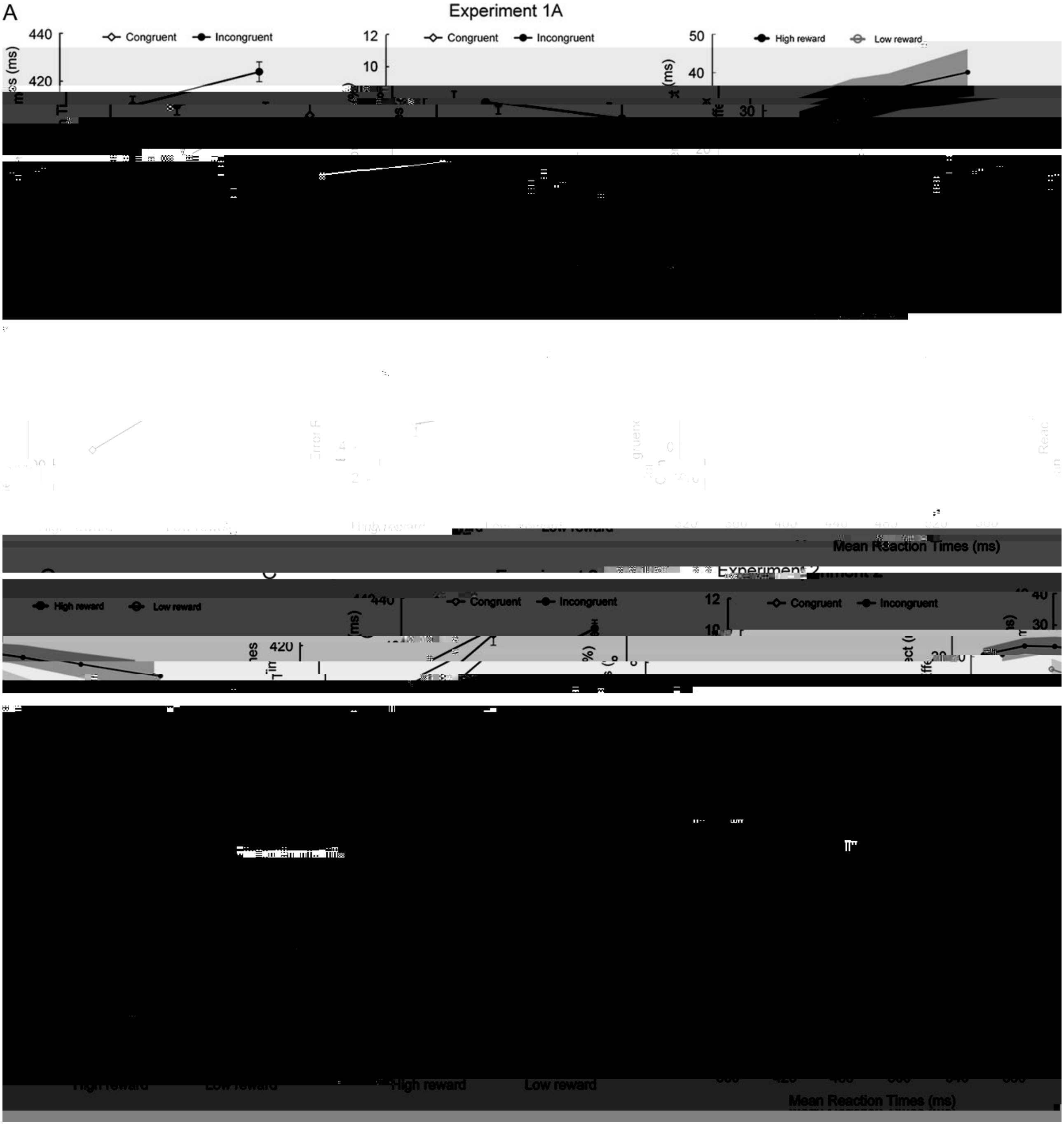

Figure 2. Behavioral results of Experiments 1A (A), 1B (B), 2 (C), and 3 (D). Left panel: mean reaction times (RT) are shown as a function of reward (high vs. low) and spatial congruency (congruent vs. incongruent). Middle panel: error rates are shown as shown as a function of reward and spatial congruency. Right panel: The congruency effects were calculated as the difference in RTs between incongruent trials and congruent trials, and are shown as a function of the mean RT in different bins for high-reward and low-reward conditions. Error bars and shades denote within-subject standard errors (Cousineau 2005).

the slope in the high-reward condition (−0.00) did not differ from zero, $t < 1$, indicating equivalent Simon effects across different response speeds (Fig. 2C, right panel). In addition, the slope in the high-reward condition was higher than the slope in the low-reward condition, $t(23) = 3.28$, $P = 0.003$.

Experiment 3 (fMRI Experiment)

The ANOVA on RTs showed a main effect of reward, $F(1, 23) = 76.68$, $P < 0.001$, $\eta_p^2 = 0.769$, with faster responses to the high-reward targets (465 ms) than to the low-reward targets (495 ms), and a main effect of spatial congruency, $F(1,23) = 111.90$, $P < 0.001$, $\eta_p^2 = 0.830$, with faster responses to the congruent targets (468 ms) than to the incongruent targets (492 ms). There was also an interaction between reward and congruency, $F(1, 23) = 15.75$, $P = 0.001$, $\eta_p^2 = 0.406$, with a larger Simon effect for the high-reward targets (35 ms) than for the low-reward targets (13 ms) (Fig. 2D, left panel). Analyses on error rates revealed only a main effect of spatial congruency, $F(1, 23) = 18.11$, $P <$

0.001, $\eta_p^2 = 0.441$, whereas neither the main effect of reward, $F < 1$, nor the interaction, $F(1, 23) = 2.92$, $P = 0.101$, reached statistical significance (Fig. 2D, middle panel).

For the distributional analysis and the model fitting, the intercept in the high-reward condition (37 ms) was larger than the intercept in the low-reward condition (18 ms), $t(23) = 3.73$, $P = 0.001$, indicating an increased Simon effect in the high-reward condition even after the effect of respan4-332.5(sta-)]TJETBT1.3984TL7.4999007.3007.s.(7i19965.F21Tf7.499900f7hadward)-447.9(-455.5(even) also a trend for a difference in LRP amplitude between high and

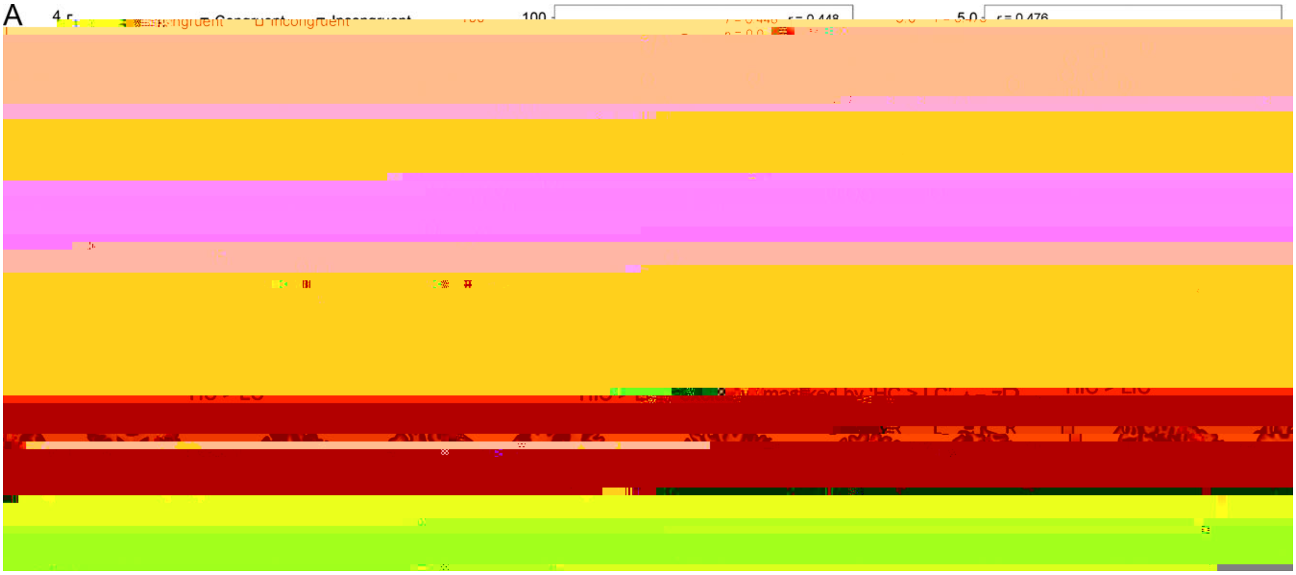

Figure 5. (A) Parameter estimates extracted from the peak voxel in M1 that contralateral to the correct response hand and the peak voxel in M1 that ipsilateral to the correct response hand are shown as the function of the 4 experimental conditions (left panel). The scatter plot (with the best-fitting regression line) illustrates the RTQ60014i5.91yg6red

difference between the HC and LC conditions) correlated with the reward-enhanced motor activation in the contralateral M1, r = 0.448, P = 0.028 (Fig. 5B, left panel). For the ipsilateral M1, there was a main effect of congruency, F(1, 23) = 6.34, P = 0.019, $\eta_p^2 = 0.216$, indicating that incongruent trials induced stronger activity in the contralateral motor cortex than congruent trials. However, the main effect of reward, F(1, 23) = 2.32, P = 0.141 and the interaction, F(1, 23) = 2.29, P = 0.144, did not reach significance. The lack of a significant interaction here might be due to the entangled reward-induced response activation and inhibition for the HIC condition (vs. LIC condition), the separation of which suffered from the poor temporal resolution of fMRI. Critically, the reward-induced inhibition strength in the ipsilateral M1 showed a correlation with the reward-induced activation strength in the contralateral M1, r = 0.476, P = 0.019 (Fig. 5B, right panel), suggesting that the individual participants' reward-induced inhibition strength was dependent on the reward-induced activation strength.

Whole-Brain Contrasts

We conducted the contrast "HIC > LIC" across the whole brain to identify areas involved in coping with the inappropriate response activation that was enhanced by reward. The contrast revealed a frontobasal ganglia network including pre-SMA, right IFC, right subthalamus where the peak voxel was localized in STN, and dorsal striatum where the peak voxel was localized in right caudate (Fig. 5B, left panel; Table 1). The reverse contrast "LIC > HIC" did not reveal any activated areas. The contrast "HC > LC" revealed the activation of right nucleus accumbens (NAcc), right IFC and posterior cingulate cortex (Fig. 5B, middle panel; Table 1). The reverse contrast "LC > HC" did not reveal any activated areas. More importantly, pre-SMA and right IFC could still be observed when the contrast "HIC > LIC" was exclusively masked by the areas activated by the contrast "HC > LC" (Fig. 5B, right panel; Table 1), suggesting the role of pre-SMA and right IFC in inhibiting the inappropriate response activation was enhanced by reward, rather than playing an augmented role in the reward-enhanced response activation.

Dynamic Causal Modeling

Figure 6A shows the exceedance probabilities derived from the Bayesian model comparison on the 7 models. The winning model was the one where only the intrinsic connectivities within the frontal areas were modulated by reward (i.e., the frontal pathway). The model parameters estimated based on the winning model are depicted in Figure 6B. Importantly for the modulatory connectivities, the HIC, but not the LIC, condition significantly enhanced the connectivity from pre-SMA to rIFC. There was no modulatory effect on the connectivity from rIFC to pre-SMA. These results suggest that the high-reward significantly enhanced the connectivity from pre-SMA to rIFC, whereas the low-reward failed to reliably alter the connectivity.

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In this study, we showed that reward can enhance automatic response activation in the motor cortex, which is overcome by active response inhibition when it conflicts with the correct response. The dynamic interactions between MFC and rIFC plays a causal role in controlling reward-induced response inhibition, suggesting an important role of the frontal cortex in motivating cognitive control (Kouneiher et al. 2009).

Reward-Induced Response Activation in the Motor Cortex

According to the dual-mechanism model, the lateral target triggers automatic response activation at the spatially corresponding hand, which causes facilitation when this activation is congruent with the task-required hand whereas it causes conflict when this activation is opposite to the task-required hand (De Jong et al. 1994; Ridderinkhof 2002). From this perspective, increased conflict for the high-reward targets in our data suggests an enhanced response activation by reward.

One alternative account could be that high-reward (vs. low-reward) targets possess higher salience (Berridge and Robinson 1998; Wang et al. 2015), which could facilitate the response to the target. Given that the Simon effect decreases as a function of response speed, the larger Simon effect in the high-reward condition relative to the low-reward condition could have appeared as a by-product of the reward-enhanced response speed. This account, however, seems to be inconsistent with the increased conflict by high-reward target after the response speed had statistically been regressed out. More importantly, in contrast to a linear decrease of response conflict for low-reward targets, which confirmed the transient nature of response activation (De Jong et al. 1994), the conflict induced by high-reward targets did not decrease with increasing RTs to the same extent as the conflict induced by low-reward targets, suggesting a sustained response activation. Taken together, our behavioral results suggest that the reward-enhanced conflict cannot be simply attributed to the facilitated responses to the high-reward targets.

The reward-induced response activation in the Simon task echoes previous studies using other cognitive control tasks. For example, Freeman et al. (2014, 2016) showed that a NoGo stim-

DCM results showed that the functional connectivity from pre-SMA to rIFC was strengthened in the HIC condition, where there was a stronger need for response inhibition. This is in line with a previous study showing increased effective connectivity between pre-SMA and right lateral prefrontal cortex when cognitive control is implemented in a reward context (Kouneiher et al. 2009). As an extension, our DCM results revealed a causal role of the connectivity from pre-SMA to rIFC control could be motivated and actively maintained during a block. By contrast in the present study, given that the reward information was unpredictable until the onset of the target in each trial, conflict control was thus recruited after detecting the incompatible response tendencies. As a result of the task

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