Reward Improves Cognitive Control Through Enhanced Signal Monitoring: Postprint

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Abstract

Cognitive control is a dynamic, process-based cognitive regulation involving two processes: monitoring and control. Previous studies have shown that reward can enhance cognitive control, but whether reward improves cognitive control by enhancing signal monitoring or by acting on the control process itself is an important question that remains to be investigated. In the present study, we designed three experiments to investigate this question. Experiment 1 adopted the Stop-Signal task to verify whether reward can enhance cognitive control; Experiment 2 isolated the signal monitoring processing of the Stop-Signal task by altering response rules, to explore whether the enhancing effect of reward in Experiment 1 originated from reward' s enhancement of signal monitoring; Experiment 3 examined the facilitative effect of attentional resource allocation on signal monitoring by manipulating attentional resource depletion. The results of Experiment 1 showed that individuals could make inhibitory responses faster based on reward information. The results of Experiment 2 indicated that in the signal monitoring task, individuals could more rapidly monitor response signals that conflicted with the current inhibitory state and were associated with reward, suggesting that reward, by enhancing the monitoring of relevant signals, helps individuals initiate responses corresponding to reward-predictive signals earlier and control conflict more efficiently. The results of Experiment 3 demonstrated that when task difficulty increased and attentional resources were depleted, the reaction time and accuracy for reward-related signals remained superior to those for non-reward signals, indicating that attentional resource allocation can modulate the monitoring speed of relevant signals. Overall, the present study demonstrates through a series of experiments that during goal-directed behavior, reward can effectively enhance cognitive control efficiency, with the key mechanism being the enhancement of relevant signal monitoring through attentional resource allocation.

Full Text

Reward Improves Cognitive Control by Enhancing Signal Monitoring

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Abstract

Cognitive control is a dynamic, process-based cognitive regulation that involves both monitoring and control processes. Previous studies have shown that reward can enhance cognitive control, but whether reward improves cognitive control by enhancing signal monitoring or by acting on the control process itself remains an important unanswered question. In this study, we designed three experiments to investigate this issue. Experiment 1 used a Stop-Signal task to verify whether reward could enhance cognitive control. Experiment 2 isolated signal monitoring processing from the Stop-Signal task by changing response rules to explore whether the enhancement effect observed in Experiment 1 originated from enhanced signal monitoring. Experiment 3 examined the role of attentional resource allocation in promoting signal monitoring by manipulating attentional resource depletion. The results of Experiment 1 showed that individuals could make inhibitory responses faster based on reward information. Experiment 2 demonstrated that in a signal monitoring task, individuals could more rapidly monitor response signals that conflicted with the current inhibitory state and were associated with reward, suggesting that reward enhances signal monitoring and helps individuals initiate responses corresponding to reward-related stimulus signals earlier and control conflict more efficiently. Experiment 3 showed that when task difficulty increased and attentional resources were depleted, response time and accuracy for reward-related signals remained superior to those for non-reward signals, indicating that attentional resource allocation can modulate the speed of signal monitoring. Overall, this series of experiments demonstrates that during goal-directed behavior, reward can effectively enhance cognitive control efficiency, with the key mechanism being enhanced signal monitoring through attentional resource allocation.

Keywords: reward; cognitive control; signal monitoring; Stop-Signal task

Cognitive control refers to the ability to suppress task-irrelevant information and impulsive behavioral tendencies during goal-directed behavior, representing an essential higher-order cognitive function required for completing cognitive activities [?, ?, ?, ?, ?, ?]. Cognitive control processing is a dynamic, process-based regulation that typically involves two processes: monitoring and control [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Individuals monitor for the appearance of conflict or warning signals during early perceptual processing stages, then implement inhibitory control. Successful inhibitory control requires individuals to quickly and effectively monitor signal appearance and subsequently make correct response selections.

Numerous studies have shown that reward, as an external stimulus incentive, can enhance cognitive control by evoking specific emotions and motivation [?, ?, ?, ?]. Compared to non-reward stimuli, individuals can effectively suppress interference from distracting stimuli and improve responses to reward-related stimuli [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. For example, Krebs, Boehler, Egner, and Woldorff (2011) employed a Stroop task and found that when target stimuli were associated with reward, individuals could more quickly and accurately exclude interference, reduce conflict, and make keypress responses. However, no previous research has investigated whether reward influences signal monitoring, while general cognitive control studies have found that conflict control depends on monitoring function [?, ?, ?]. Signal monitoring differs from response control in terms of function: signal monitoring is primarily responsible for detecting and searching for signals relevant to target behavior within the visual field, then transmitting relevant information to response control, while response control maintains goal-relevant behaviors and suppresses goal-irrelevant behaviors. In terms of the execution process of cognitive control, signal monitoring occurs at an early stage of attentional processing, preceding response control. Previous research has shown that effective monitoring of conflict signals during goal-directed behavior optimizes subsequent response output [?, ?, ?, ?, ?, ?, ?]. So does reward enhance cognitive control by strengthening signal monitoring—whereby reward-related stimuli capture more attention, enabling individuals to monitor reward-related signals faster and initiate inhibitory responses earlier—or does it act directly on cognitive control functions by enhancing stimulus-response mappings, allowing individuals to extract corresponding response rules faster when facing reward-related stimuli? Previous tasks used to examine cognitive control (e.g., Go/NoGo, Flanker, Stroop) reflect both signal monitoring ability and conflict control ability. Therefore, when investigating reward enhancement of cognitive control, previous studies could not provide direct evidence indicating whether the enhancement effect originated from enhanced signal monitoring [?, ?, ?, ?, ?, ?].

In cognitive research, the Stop-Signal task is a commonly used paradigm for studying cognitive control. In this paradigm, stop signals are low-probability events whose onset latency is dynamically adjusted based on participants' responses. When a stop signal suddenly appears, individuals must allocate attention appropriately during the response process, quickly monitor signal appearance, and then halt the already-prepared response [?, ?, ?, ?]. Faster monitoring of stop signal appearance enables earlier initiation of stopping responses and suppression of keypress impulses. Due to its relatively simple processing involving only stop signal monitoring and inhibition, and because it can calculate individuals' stop signal response times based on experimental design and performance to effectively assess cognitive control ability, this study employs the Stop-Signal task to measure reward' s facilitative effect on stop signal processing and thereby examine the mechanism through which reward enhances cognitive control.

Furthermore, reward presentation methods have different effects on cognitive control. Previous studies manipulated reward information by presenting reward cues before each trial (block). Under this manipulation, reward primarily induced a sustained preparatory state in participants, actively maintained goal information, and further regulated individuals' ability to resolve conflict and inhibit responses [?, ?, ?, ?, ?, ?]. Since this method required participants to continuously maintain reward-related cue information before responding, it consumed more cognitive resources, created high cognitive load, affected operation of the experimental task itself, and could not accurately examine the mechanism of reward' s influence on stimulus signal processing itself.

Therefore, this study adopts a stimulus-reward association method on the basis of the Stop-Signal task to associate one or more types of stimuli with reward, thereby examining the mechanism through which reward enhances cognitive control. Unlike the influence mechanism of reward cues, stimulus-reward association affects individuals' attentional processing of immediately appearing target-related information, further optimizing behavioral output [?, ?, ?]. Additionally, this study employs three experiments to explore the mechanism that reward enhances cognitive control by strengthening signal monitoring. In Experiment 1, we examine reward' s enhancement effect on cognitive control through the Stop-Signal task. While Experiment 1's results can demonstrate that reward enhances cognitive control, they cannot reflect whether the enhancement effect originates from enhanced monitoring function or control function. Based on Experiment 1' s results, Experiment 2 changes response rules in the Stop-Signal task, requiring participants to make no response (Stop) to left/right arrows. At this point, participants are in an activated inhibitory state, then a low-probability response signal (Go) is given, requiring participants to make fast and accurate keypress responses. This processing is identical to the stop signal processing in the Stop-Signal task, where already-formed response tendencies (Go/Stop) conflict with response activities represented by low-probability stimulus signals (Stop/Go). Unlike traditional Stop-Signal tasks, in Experiment 2, individuals monitor Go signal appearance and immediately initiate keypress responses, with response time reflecting signal monitoring. Furthermore, previous research has shown that reward information can enhance individuals' processing of stimulus signals by modulating attentional resource allocation [?, ?, ?, ?, ?, ?, ?, ?, ?]. Experiment 3 adds stop signals based on Experiment 2' s rules. Since processing stop signals occupies attentional processing resources for Go signals, if reward stimuli can attract more attentional resources to enhance signal monitoring processing, then even under attentional resource depletion, reward-related signals can still attract more attentional resources and show superior behavioral performance compared to non-reward stimuli.

2.1 Participants

Twenty-six individuals (12 males, aged 17-24 years, mean age 20.5 years) participated in the experiment. All participants were volunteers with normal physical and mental health, right-handed, normal or corrected-to-normal vision, and no color blindness or weakness. Participants signed informed consent forms before the experiment and received corresponding compensation based on their task performance after completion.

2.2 Apparatus

The experiment used a computer to present stimuli on a 17-inch Dell E2014HC monitor with a resolution of 1600×900 and a refresh rate of 60 Hz. The experimental program was compiled and run using E-Prime. Participants made keypress responses on a keyboard, with reaction time and accuracy automatically recorded by the computer. Participants sat approximately 60 cm from the screen and completed the experiment individually in a moderately lit single-room laboratory.

2.3 Tasks and Procedure

This study consisted of three experiments. The stimuli and procedure for each experiment are shown in Figure 1 [Figure 1: see original paper]. First, a "+" was presented at the center of the screen for 500 ms, followed by a leftward or rightward white arrow. Occasionally, an upward or downward triangle of different colors (blue or yellow) would appear on the arrow. Participants were required to make keypress responses according to the response rules for each experimental part, followed by a blank screen for 500-1000 ms before the next trial began.

Figure 1 Experimental procedure diagram. A: In Experiment 1, participants judged arrow direction; when an upward or downward triangle (stop signal) appeared on the arrow, they stopped responding. B: In Experiment 2, participants made no response to the arrow; when an upward or downward triangle (Go signal) appeared on the arrow, they judged arrow direction. C: In Experiment 3, participants made no response to the arrow or when a downward triangle (stop signal) appeared on the arrow; when an upward triangle (Go signal) appeared on the arrow, they judged arrow direction.

Experiment 1 was a Stop-Signal task that primarily examined participants' inhibitory ability. When a leftward or rightward arrow appeared on the screen, participants were required to quickly and accurately judge the arrow' s direction, pressing the "F" key for leftward arrows and the "J" key for rightward arrows. When an upward or downward triangle appeared on the arrow, participants were required to stop keypressing and make no response.

Experiment 2 changed the response rules of the Stop-Signal task to examine participants'monitoring of signal stimuli. The task required participants to make no keypress response when a leftward or rightward arrow appeared on the screen. When an upward or downward triangle appeared on the arrow, participants were required to quickly and accurately judge the arrow' s direction, pressing the "F" key for leftward arrows and the "J" key for rightward arrows.

Experiment 3 included both signal inhibition rules and signal response rules. Participants were required to make no keypress response when a leftward or rightward arrow or a downward triangle appeared on the arrow. When an upward triangle appeared on the arrow, participants were required to quickly and accurately judge the arrow' s direction, pressing the "F" key for leftward arrows and the "J" key for rightward arrows.

Before the experiment, participants were informed that they would first receive 30 RMB for participating, but their final compensation would depend on their performance during the experiment. To prevent participants from being distracted by calculating monetary amounts and affecting experimental operation, this study converted all monetary amounts into game coins for manipulation (100 game coins = 0.1 RMB) [**?**, **?**, **?**, **?**]. Correct responses to yellow triangle (upward or downward) signals according to response rules earned 100 game coins each time, while incorrect responses deducted 100 game coins. Correct responses to blue triangle (upward or downward) signals earned 0 game coins each time, with incorrect responses deducting 0 game coins. Previous research found that different colored stimuli affect cognitive control [**?**, **?**, **?**, **?**, **?**], so the correspondence between colors and reward magnitude was balanced between participants. Participants could take short breaks after each block or experimental part to maintain optimal state.

In Experiment 1, the time interval between stop signals and Go signals (i.e., stop signal delay, SSD) was set using a tracking algorithm. The initial SSD was 200 ms, then dynamically adjusted based on participants' responses: if participants successfully inhibited their response on the current stop trial, the SSD for the next Stop trial increased by 34 ms to increase inhibition difficulty; if participants failed to inhibit their response on the current stop trial, the SSD for the next Stop trial decreased by 34 ms to increase the likelihood of inhibition. This tracking algorithm caused SSD to change dynamically in a staircase manner, ensuring participants successfully inhibited 50% of stop trials. If participants failed to inhibit, the stop signal disappeared after their keypress; if inhibition was successful, the stop signal presentation time was (1000 - SSD) ms. In Experiments 2 and 3, the time interval between triangle signals and arrows (signal delay, SD) varied randomly, with the variation range set at 312 ± 115 ms based on previous research [**?**, **?**, **?**, **?**, **?**].

Experiment 1 and Experiment 2 each had 270 trials (each experiment consisted of three blocks). In each experiment, triangle signals appeared 90 times (45 reward signals, accounting for 17% of total trials; 45 non-reward signals, accounting for 17% of total trials). Experiment 3 had 360 trials (consisting of four blocks), with triangle signals appearing 120 times (30 Go and 30 Stop reward signals each, accounting for 8% of total trials each; 30 Go and 30 Stop non-reward signals each, accounting for 8% of total trials each). Each experiment had 30 practice trials beforehand, with triangle appearance probability at 50% during practice (reward and non-reward trials each accounting for 50%). After each practice session, participants were required to verbally report whether they had mastered the response rules and the reward amounts represented by different colors. If participants had not mastered the response or reward rules, they were required to practice again. Additionally, to avoid confusion about triangle signal responses across different experimental rules, the order of Experiments 1, 2, and 3 was fixed. All trials were presented in pseudorandom order, with triangle signals not appearing consecutively more than twice.

Stop signal reaction time (SSRT) is a key measure of inhibitory ability in the Stop-Signal task. This study used the relatively more precise integration method to estimate SSRT. Assuming n is the probability of error responses in Stop trials and t is the number of correct responses in Go trials, Go RTs were sorted from fastest to slowest. SSRT = the Go RT at the n×t position - mean SSD [**?**, **?**, **?**, **?**, **?**]. Statistical indicators for Go signals and stop signals are shown in Table 1 .

Table 1 Behavioral data for Experiment 1 Stop-Signal task (M ± SD)

Measure	Non-reward trials	Reward trials
Stop signal SSD (ms)	236 ± 85	247 ± 88
Stop signal SSRT (ms)	233 ± 73	220 ± 73
Stop signal accuracy	0.51 ± 0.06	0.51 ± 0.07
Go trial RT (ms)	493 ± 77	
Go trial accuracy	0.98 ± 0.02	

In Experiment 1, accuracy for both reward and non-reward stop trials was close to 50%, with no significant difference between the two groups, $t(25) = 0.70$, $p > 0.05$, indicating that the tracking algorithm used in this experiment was effective. SSD was calculated using the tracking algorithm for reward and non-reward stop trials separately. SSD for reward trials was significantly greater than for non-reward trials ($t(25) = 2.85$, $p < 0.01$, Cohen’ s $d = 1.14$), and SSRT for reward trials was significantly shorter than for non-reward trials ($t(25) = 2.20$, $p < 0.05$, Cohen’ s $d = 0.88$), indicating that reward information accelerated inhibitory responses and shortened stop signal reaction time.

Analysis (see Figure 2A) showed that individuals monitored reward signals significantly faster than non-reward signals, $t(25) = 2.13$, $p < 0.05$, Cohen’ s $d = 0.85$; the difference in accuracy between the two was not significant, $t(25) = 0.43$, $p > 0.05$.

Figure 2 [Figure 2: see original paper] Experimental results. A: Reaction time and accuracy for signal monitoring in Experiment 2; B: Comparison of reaction time and accuracy for Go trials between Experiment 2 and Experiment 3

Comparing Go trial performance between Experiment 3 and Experiment 2 examined attentional resource allocation. Separate 2 (experiment sequence: Experiment 2, Experiment 3) × 2 (reward information: reward signal, non-reward signal) repeated measures ANOVAs were conducted on Go trial reaction time and accuracy (see Figure 2B). Analysis of reaction time revealed a significant main effect of reward information, F(1, 25) = 11.20, $p < 0.01$, $^2 = 0.309$, with reward trial RT (395 ± 7.49 ms) significantly faster than non-reward trial RT (412 ± 7.51 ms). The main effect of experiment sequence was also significant, F(1, 25) = 63.50, $p < 0.001$, $^2 = 0.718$, with mean RT in Experiment 3 (439 ± 7.36 ms) significantly longer than in Experiment 2 (368 ± 9.34 ms). The interaction was not significant, $p > 0.05$. Additionally, analysis based on accuracy revealed a significant main effect of reward information, F(1, 25) = 11.75, $p < 0.01$, $^2 = 0.32$, with reward trial accuracy (0.95 ± 0.01) significantly greater than non-reward trial accuracy (0.87 ± 0.02). The main effect of experiment sequence was significant, F(1, 25) = 8.87, $p < 0.01$, $^2 = 0.26$, with accuracy in Experiment 3 (0.88 ± 0.02) significantly lower than in Experiment 2 (0.94 ± 0.01). The interaction was significant, F(1, 25) = 7.36, $p < 0.05$, $^2 = 0.23$. Simple effects analysis indicated that only in Experiment 3 was the difference in accuracy between reward and non-reward trials significant. Further calculation and comparison of the difference in Go trial accuracy from Experiment 2 to Experiment 3 revealed that the accuracy difference for non-reward trials (0.13 ± 0.2) was significantly greater than for reward trials (0.03 ± 0.06), t(25) = 2.85, $p < 0.01$, Cohen' s d = 1.14.

Individuals' attentional resources gradually become depleted as the experiment progresses, requiring them to balance speed and accuracy during task processing. Based on this, analysis of Experiment 3 showed (see Figure 3A [Figure 3: see original paper]) that in Go signal trials corresponding to triangles, reward signal RT was significantly faster than non-reward signal RT (t(25) = 2.79, $p < 0.01$, Cohen' s d = 1.12), and reward stimulus accuracy was significantly higher than non-reward stimulus accuracy (t(25) = 2.93, $p < 0.01$, Cohen' s d = 1.72). In contrast, in stop signal trials corresponding to triangles, reward stimulus accuracy was significantly lower than non-reward stimulus accuracy (t(25) = 3.12, $p < 0.01$, Cohen' s d = 1.25). Furthermore, Experiment 3 was divided into early blocks (blocks 1-2) and late blocks (blocks 3-4) (see Figure 3B). A 2 (block: early, late) × 2 (reward information: reward signal, non-reward signal) repeated measures ANOVA on stop signal accuracy revealed a significant main effect of reward, F(1, 25) = 9.95, $p < 0.01$, $^2 = 0.285$, with non-reward stimulus accuracy (0.97 ± 0.01) significantly higher than reward stimulus accuracy (0.91 ± 0.02). The main effect of block was not significant ($p > 0.05$), indicating no significant difference in stop signal accuracy between early and late blocks, and the interaction between block and reward information was not significant ($p > 0.05$). A 2 (block: early, late) × 2 (reward information: reward signal, non-reward signal) repeated measures ANOVA on Go signal RT revealed a significant main effect of reward, F(1, 25) = 7.55, $p < 0.05$, $^2 = 0.205$, with reward signal RT (430 ± 7.32 ms) significantly shorter than non-reward signal RT (448.40

± 9.51 ms). The main effect of block was not significant, but the interaction between reward information and block was significant, F(1, 25) = 5.37, $p < 0.05$, $^2 = 0.177$. In early blocks, reward signal RT (418 ± 9.90 ms) was significantly faster than non-reward signal RT (448 ± 11.38 ms), while in late blocks, the difference between reward signal RT (441 ± 8.41 ms) and non-reward signal RT (448 ± 9.32 ms) was not significant. A 2 (block: early, late) × 2 (reward information: reward signal, non-reward signal) repeated measures ANOVA on Go trial accuracy revealed a significant main effect of reward, F(1, 25) = 8.49, $p < 0.01$, $^2 = 0.232$, with reward stimulus accuracy (0.93 ± 0.01) significantly higher than non-reward stimulus accuracy (0.85 ± 0.03). However, the main effect of block and the interaction between reward information and block were not significant ($p > 0.05$).

Figure 3 [Figure 3: see original paper] Experimental results. A: Accuracy for Stop trials, accuracy and reaction time for Go trials in Experiment 3; B: Reaction time, accuracy for Go trials, and accuracy for Stop trials in early and late blocks of Experiment 3

This study examined the enhancement mechanism of reward on cognitive control based on the Stop-Signal task. In the Stop-Signal task, individuals could inhibit reward-related signals faster than non-reward signals. This is consistent with previous research findings [**?**, **?**, **?**, **?**], showing that reward improves behavioral performance in cognitive control-related tasks, indicating that reward can enhance individuals' cognitive control ability. Unlike previous studies that used "reward cues" to induce a sustained preparatory state to enhance cognitive control, this study employed a stimulus-reward association presentation method, so the enhancement effect of reward primarily originated from reward' s influence on the processing of stimulus signals themselves.

Cognitive control processing is a process-based cognitive regulation. fMRI studies have shown that conflict signals activate the anterior cingulate cortex (ACC), which is responsible for signal monitoring. Subsequently, ACC transmits signals to the dorsolateral prefrontal cortex (dlPFC), which is responsible for control processing, enabling our brains to better complete tasks [**?**, **?**, **?**, **?**, **?**]. This study focuses on the specific processes involved in cognitive control processing through the Stop-Signal task, examining the influence of reward on signal monitoring and response control. Experiment 1' s results showed that SSRT for reward-related stop signals was shorter, indicating that individuals could initiate inhibitory responses to reward-related signals more quickly. The horse-race model [**?**, **?**] assumes that inhibitory response occurrence depends on the competition between the stop response triggered by the stop signal and the keypress response triggered by the Go signal. If the stop response completes before the Go response, behavioral inhibition is achieved; conversely, if the Go response completes before the stop response, inhibition fails. Further research using MEG has found that the competition outcome between Go and stop responses depends on individuals' monitoring of Go and stop signals during early perceptual processing stages [**?**, **?**]. Faster monitoring of stop signal appearance enables earlier initiation of stop responses and implementation of keypress behavior inhibition. Salinas and Stanford (2013) recently used psychophysical methods and similarly found that in stop signal tasks, individuals' successful implementation of inhibitory responses depends on rapid and effective monitoring of stop signals during early perceptual processing stages. These research findings all demonstrate that attentional processing of task-relevant stimulus signals during early perceptual processing stages is one of the key factors for enhancing inhibitory control [?, ?, ?]. Meanwhile, numerous studies have shown that reward can enhance perceptual representations of relevant stimuli during early attentional processing, enabling individuals to monitor reward-related signal appearance faster [?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Experiment 2 of this study found that when individuals were in an already-activated inhibitory state and a sudden non-reward/reward signal conflicting with current response tendencies required a response, reward-related signals had shorter RTs, indicating that reward-related signals could be monitored faster, followed by keypress responses. From this, we infer that during stop signal processing, compared to non-reward signals, reward-related stop signals can be monitored faster by individuals, stop responses are initiated and completed before Go responses, and responses are successfully inhibited. This inference is supported by EEG research, which found that in Stop signal tasks, N1 amplitude was larger in successfully inhibited trials compared to failed inhibition trials. The N1 component is related to visual attention for specific targets [?, ?, ?], while reward-related stop signals can evoke larger N1 amplitudes during perceptual processing stages [?, ?], indicating that reward can enhance signal monitoring during early perceptual processing stages, enabling individuals to initiate inhibitory responses to reward-related signals faster in Stop-Signal tasks.

Additionally, similar to the current study, research examining the influence of emotional faces on Stop-Signal tasks found that compared to neutral faces, participants could make inhibitory responses to negative emotional faces (anger, sadness, etc.) faster, with shorter SSRTs for negative faces. The authors proposed that this phenomenon occurred because negative faces enhanced their perceptual representations during perceptual processing stages, facilitating relevant signal monitoring [?, ?, ?, ?, ?]. Research from perceptual processing has shown that both reward stimuli and negative emotional faces demonstrate superior task performance in visual search, spatial orienting, and other paradigms compared to neutral/non-reward stimuli, indicating that both reward stimuli and negative emotional faces receive enhanced processing during early perceptual stages, enabling individuals to monitor such stimuli faster [?, ?, ?]. Combined with the results of this study, we propose that the shorter SSRT for reward signals compared to non-reward signals is due to individuals monitoring reward-related signals faster, thereby further enhancing behavioral inhibition ability.

It should be noted that although this study used a reward-stimulus association method to examine how reward improves task-related performance through its influence on signal processing itself, the motivational effect of reward on cognitive control cannot be completely excluded. Pessoa (2009) proposed that reward motivation can modulate attentional resource allocation, thereby producing processing-specific effects. In Experiments 2 and 3, Go trial performance for reward trials was superior to non-reward trials, and in Experiment 2 with simple rules, there was no difference in accuracy between reward and non-reward trials. However, in Experiment 3 with complex rules, reward accuracy was significantly greater than non-reward trials, indicating that even when other processing occupied some attentional resources, reward-related stimuli still attracted more attentional resources to ensure accuracy. In early and late stages of Experiment 3, attentional resources were depleted during task processing, yet RT and accuracy for non-reward Go trials showed no obvious changes during this process, indicating that individuals used limited attentional resources to process non-reward signals, and processing of non-reward signals was already at the minimum execution level, so attentional resource depletion had no effect on them. In contrast, reward-related signals occupied more attentional resources. With attentional resource depletion, individuals had to balance speed and accuracy to obtain more rewards, so they slowed responses to reward signals in late blocks to ensure accuracy for both Go and stop trials. Overall, explicitly informing participants that responding to targets of one color would yield reward led them to consciously associate colors with different reward levels, potentially creating stronger response motivation for reward-related colored signals. Meanwhile, reward motivation allocated more attentional resources to process reward-related stimuli. Furthermore, research has shown that reward motivation promotes dopamine release [?, ?, ?], while dopamine enhances the perceptual representation of reward-associated stimuli in the nervous system [?, ?, ?]. Based on this, we propose that under the reward-stimulus association presentation method, reward motivation may further enhance cognitive control by enhancing relevant signal monitoring through attentional resource allocation.

Reward motivation has a very important influence on behavior occurrence. Notably, reward can both enhance and impair target behavior performance. Previous research using stop signal tasks found that when reward availability was associated with Go signals—informing participants that they could only obtain reward by correctly and quickly judging arrow direction in reward blocks—participants judged arrow direction faster than in non-reward blocks, but SSRT for stop signals was longer, indicating that reward impaired response control. This occurred because when reward was associated with Go signals, individuals allocated more attentional resources to process Go trials to maximize gains. Meanwhile, during competition between Go and stop responses, reward accelerated individuals' initiation of Go responses, increasing inhibition failure rates and lengthening SSRT [?, ?]. In Experiment 1 of this study, reward availability was primarily associated with stop signal responses, and results showed that reward could enhance response inhibition. This indicates that when reward-driven behavior direction aligns with target behavior direction, reward strengthens representation and occurrence of goal-directed behavior and enhances target behavior performance. Conversely, when reward-driven behavior direction conflicts with goal-directed behavior direction, reward impairs goal behavior occurrence.

This viewpoint has been extensively demonstrated in attention research. For example, studies found that when reward was associated with target stimuli, individuals could focus attention on target stimuli faster and make correct and rapid keypress responses. In contrast, when reward was associated with distracting stimuli, excessive attentional focus on distracting stimuli caused by reward interfered with individuals' identification of and response to target stimuli, leading to decreased accuracy and increased RT [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Researchers believe this occurs because reward enhances early perceptual representation of relevant stimulus signals, thereby affecting individuals' response output [?, ?]. Interestingly, in Experiment 3 of this study, when reward was associated with both Go and stop signals, results showed that accuracy for reward-related stop signals was significantly lower than for non-reward-related stop signals, while responses to reward-related Go signals were superior to non-reward-related Go signals. This is because during human evolution and development, reward has typically been associated with approach behavior. Participants seeing reward signals would impulsively make approach responses [?, ?, ?, ?, ?], which aligns with the direction of keypress response occurrence. Therefore, reward-related Go signals had shorter RTs and higher accuracy. However, during conversion between inhibitory and response rules, after experiencing Go response rules, inhibiting stop signals required stronger response control, especially when processing reward-related stop signals. Participants needed to regulate the conflict between motivation and response, making inhibition of reward-related stop signals more difficult. Consequently, accuracy for reward stop signals was lower than for non-reward stop signals. This is consistent with Freeman and Aron' s (2016) findings using Go/No-Go tasks, which showed that when reward information was associated with both Go and No-Go signals, reward accelerated Go response speed but decreased No-Go response accuracy.

In summary, this study demonstrates through three experiments that during goal-directed behavior, the reward system can drive goal-oriented behavior. Reward-related signals attract more attentional resources, enhance signal monitoring, and further improve cognitive control. Furthermore, this study' s demonstration of the mechanism through which reward enhances cognitive control provides new perspectives and insights for future research on reward and cognitive control. Future studies should not only explore the processing mechanisms of reward motivation and its intensity in reward' s influence on cognitive control but also focus on group differences in the interaction between signal monitoring, conflict control, and reward. Based on this study' s finding that reward can enhance individuals' inhibitory response speed to stop signals, future research could propose training and intervention programs targeting monitoring and control functions separately to achieve effective enhancement of cognitive control ability.

The results of this study show that individuals in the Stop-Signal task can inhibit stop signals faster based on reward information, indicating that reward can enhance cognitive control. To examine reward' s influence on signal monitoring, we further changed response rules, requiring individuals to make immediate keypress responses after monitoring signals. Results showed that reward-related signals had shorter RTs, indicating that individuals could monitor reward-related signals faster. Additionally, by increasing experimental rule difficulty and depleting attentional resources, we demonstrated that reward-related signals attract more attentional resources, thereby optimizing behavior occurrence and output. Since in cognitive control processing, individuals first monitor signals then implement control, and the task we used to examine signal monitoring shares the same processing as the Stop-Signal task—both involve responding to low-probability signals that conflict with currently activated states—our results demonstrate that reward can enhance individuals' monitoring of relevant stimuli by modulating attentional resource allocation, thereby further enhancing cognitive control.

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Note: Figure translations are in progress. See original paper for figures.