

Utilization of reward-prospect enhances preparatory attention and reduces stimulus conflict

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Published online: 13 May 2014
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Abstract The prospect of gaining money is an incentive widely at play in the real world. Such monetary motivation might have particularly strong influence when the cognitive system is challenged, such as when needing to process conflicting stimulus inputs. Here, we employed manipulations of reward-prospect and attentional-preparation levels in a cued-Stroop stimulus conflict task, along with the high temporal resolution of electrical brain recordings, to provide insight into the mechanisms by which reward-prospect and attention interact and modulate cognitive task performance. In this task, the cue indicated whether or not the participant needed to prepare for an upcoming Stroop

stimulus and, if so, whether there was the potential for monetary reward (dependent on performance on that trial). Both cued attention and cued reward-prospect enhanced preparatory neural activity, as reflected by increases in the hallmark attention-related negative-polarity ERP slow wave (contingent negative variation [CNV]) and reductions in oscillatory Alpha activity, which was followed by enhanced processing of the subsequent Stroop stimulus. In addition, similar modulations of preparatory neural activity (larger CNVs and reduced Alpha) predicted shorter versus longer response times (RTs) to the subsequent target stimulus, consistent with such modulations reflecting trial-to-trial variations in attention. Particularly striking were the individual differences in the utilization of reward-prospect information. In particular, the size of the reward effects on the preparatory neural activity correlated across participants with the degree to which reward-prospect both facilitated overall task performance (shorter RTs) and reduced conflict-related behavioral interference. Thus, the prospect of reward appears to recruit attentional preparation circuits to enhance processing of task-relevant target information.

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Keywords Attention · Motivation · Event-related potentials ·
Contingent negative variation (CNV) · Oscillatory Alpha

Introduction

We navigate through life in complex, dynamic environments, in which the relevance of information around us changes continuously. To efficiently deal with these changes, we use attentional-control processes to select that stimulus information that is most important to us at each moment, resulting in improved task performance on those inputs (Pashler, 1998). It is also the case that the possibility of gaining reward, monetary or otherwise, tends to improve task performance, as has been shown in terms of shorter response times (RTs) and higher accuracy (Bijleveld,

Custers, & Aarts, 2010), improved visual cognition (Engelmann, Damaraju, Padmala, & Pessoa, 2009; Engelmann & Pessoa, 2007; Kristjánsson, Sigurjónsdóttir, & Driver, 2010), better cognitive control (Locke & Braver, 2008), and improved memory (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Krebs, Schott, Schütze, & Düzel, 2009; Wittmann et al., 2005). Neuroimaging studies have shown some overlap in brain areas that are activated by reward-prospect and those regions implicated in attentional control, suggesting a relation between these two cognition-influencing factors (Bendiksby & Platt, 2006; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Hickey, Chelazzi, & Theeuwes, 2010; Krawczyk, Gazzaley, & D'Esposito, 2007; Krebs, Boehler, Appelbaum, & Woldorff, 2013; Krebs, Boehler, Egner, & Woldorff, 2011; Krebs, Boehler, Roberts, Song, & Woldorff, 2012; Maunsell, 2004; Pessoa & Engelmann, 2010). Although attentional control and reward-prospect both seem to modulate the way we cope with continuously changing environmental input and goals, the nature of the interactions between these factors remains elusive.

One key way in which attention and reward-prospect seem to interact is in the wide range of preparatory processes that we need to continually perform to most effectively navigate through our environment, as that environment and our goals change from moment to moment. In fMRI studies, attentional preparation has been shown to be reflected in activation of the fronto-parietal attentional-control network, prior to the performance of a task, particularly demanding ones (reviewed in Corbetta & Shulman, 2002). Electrophysiologically, attentional preparation has been found to be associated with an enhancement of the fronto-central negative-polarity ERP wave known as the contingent negative variation (CNV; Walter, Cooper, Aldridge, McCallum, & Winter, 1964), which has been explicitly linked to activity in the fronto-parietal attentional-control network observed with fMRI (Grentt-Jong & Woldorff, 2007). Another classical marker for increases in attention and attentional preparation are reduced levels of Alpha-band (8–12 Hz) oscillatory EEG activity (Foxe & Snyder, 2011; Grentt-Jong, Boehler, Kenemans, & Woldorff, 2011), both globally when an individual is less attentive and more specifically for local cortical circuits (Worden, Foxe, Wang, & Simpson, 2000), although the relationship of these effects to attention-related CNV modulations is not well understood.

Preparatory attention is not consistently implemented across time, however, which can be observed experimentally by its variation across trials in an experimental session. For instance, Hillyard (1969) showed a strong correlation between preparatory activation, as reflected by the CNV, and within-subjects RT performance, suggesting that the CNV reflects a “common and ubiquitous” preparatory effect. Similarly, using fMRI in a cognitive conflict task, Weissman, Roberts, Visscher, and Woldorff (2006) showed that decreased prestimulus activity levels in frontal attentional-control areas were associated with longer RTs, presumably due to trial-to-trial attentional variations. It is also the case that within-subjects performance can be predicted

by prestimulus fluctuations in oscillatory EEG activity in the Alpha (8–12 Hz) frequency band (Hanslmayr et al., 2007). These various studies indicate that variations in these neural markers of attentional preparation can predict trial-by-trial variations in within-subjects behavioral performance.

Preparatory attentional control can also be influenced by cued reward-prospect. For example, in a recent fMRI study, Padmala and Pessoa (2011) cued reward-prospect in a Stroop-like stimulus conflict task in which the cue on each trial indicated whether there was a prospect of reward on that trial. The classic behavioral finding in Stroop-like conflict tasks is that participants are slower to respond on incongruent trials than on congruent ones (MacLeod, 1991; Stroop, 1934). In the Padmala and Pessoa study, the reward-prospect cuing resulted in a reduction of the interference cost measured behaviorally for the subsequent target stimuli (incongruent-trial RT vs. neutral-trial RT [neutral targets stimuli did not contain conflicting information]). In addition, the cues indicating reward-prospect elicited enhanced activity in the fronto-parietal attentional-control network, as well as in subcortical regions such as the ventral striatum (including the nucleus accumbens) that have been associated with the processing of reward (Aarts, Holstein, & Cools, 2011; Camara, Rodriguez-Fornells, & Münte, 2008; Delgado, 2007; Haber & Knutson, 2010; Knutson, Adams, Fong, & Homme, 2001; Schultz, 2000). The modulations of these neural markers of attention by reward-prospect suggest that one key way that the latter might influence behavior is by marshalling the attentional control network.

Another method for manipulating reward-prospect, in contrast to advance cuing, is to use within-trial reward associations, such that specific stimuli or stimulus features of the task itself are associated with reward or not. For example, in a recent series of stimulus conflict studies (Krebs et al., 2013; Krebs et al., 2011; Krebs, Boehler, & Woldorff, 2010), a modified version of the color-naming Stroop task was used in which certain font colors were associated with reward-prospect, while others were not. In the fMRI version of this paradigm (Krebs et al., 2011), the findings indicated enhanced fMRI activity in both the frontal-parietal control network and the ventral striatum when Stroop stimuli that were associated with reward were processed, again implying important functional interactions between reward processing (here, within-trial reward associations) and attentional control. Behaviorally, these studies also found that conflict-induced behavioral interference was reduced for reward-associated Stroop stimuli, in addition to such stimuli producing shorter overall RTs. And lastly, in the electrophysiological version of this paradigm (Krebs et al., 2013), it was found that reward associations led to an earlier instantiation of the negative-polarity ERP incongruity effect that is typically observed in an incongruent-stimulus versus congruent-stimulus contrast (the Ninc/N450; Hanslmayr et al., 2008; Liotti, Woldorff, Perez, &

Mayberg, 2000). Such a result suggests that reward associations can induce accelerated conflict detection, followed by reduced behavioral interference effects. It is not known, however, whether such effects would occur when the prospect of reward is cued in advance, rather than by stimulus associations, or whether such effects would also be observed just in response to attentional cuing.

Task manipulation and hypotheses of the present study

To investigate the relationships between attentional control, reward, and behavioral performance, we implemented reward-prospect cuing in a stimulus conflict Stroop task while measuring high temporal resolution EEG recordings of brain activity, with a particular focus on the cue-elicited electrophysiological markers closely associated with attentional preparation (i.e., cue-triggered CNV and Alpha activations). We used three manipulations. The first was cuing to prepare versus not prepare, by including trials that began with a cue indicating that a target would appear on that trial and trials that began with a control-condition cue indicating that no target would appear, similar to several previous attentional cuing paradigms using both ERPs and fMRI (Grent-‘t-Jong & Woldorff, 2007; Woldorff et al., 2004). The second manipulation, for trials on which a target would be appearing, was cuing whether there was reward-prospect versus no-reward-prospect, similar to the fMRI study of Padmala and Pessoa (2011), but now while recording electrophysiological measures of brain activity. These two manipulations allowed us to extract in the same study and participants the effect of cuing for reward-prospect versus cuing for attentional preparation. Third, we looked at trial-by-trial variations in attentional preparatory activity as associated with trial-to-trial variations in task performance (short vs. long RTs) in order to relate these to neural preparatory activity associated with reward-prospect. Thus, this approach provided three cognitive manipulations (attend vs. not attend, reward-prospect vs. no-reward-prospect, and trial-to-trial variations in performance), which we hypothesized would all induce modulations of the classic neural markers (CNV and Alpha) associated with attentional preparation. Moreover, this approach enabled us to also leverage the high temporal resolution of EEG and ERP recordings to relate these cue-elicited variations in brain activity with modulation of behavioral performance and neural activations for the target Stroop stimulus that followed.

More specifically, in response to the cues, we expected that the identification of a cue stimulus indicating reward-prospect, as compared with no-reward-prospect, would be associated with a larger occipital N2 wave, due to its presumed greater salience (Folstein & Van Petten, 2008; Hickey & Zoest, 2012; Krebs et al., 2013). More importantly here, however, we expected that the cuing for attentional preparation (for both reward-prospect and no-reward-prospect) versus cuing to not prepare (control cues) would elicit enhanced CNVs and

decreased Alpha activity prior to the target Stroop stimulus. We also expected that comparison of cuing for reward-prospect versus cuing for no-reward-prospect would also elicit an enhanced CNV and decreased Alpha activity, due to the marshalling of the attentional control circuits. In addition, we hypothesized that the CNV would be larger and Alpha would be more decreased when followed by fast responses versus slow responses to the target Stroop stimulus, although these effects might differ depending on whether the trial included reward-prospect or not.

Following the cue, we also anticipated a number of related behavioral and neural effects on the processing of the subsequent target Stroop stimuli. First, behaviorally, we expected shorter RTs and fewer errors for congruent than for incongruent Stroop stimuli, as has been classically shown, as well as for reward-prospect trials versus those without such prospect. In addition, we hypothesized that we might observe a reduced behavioral interference effect (incongruent RTs vs. congruent RTs) for reward-prospect trials versus no-reward-prospect trials, as has been found in some previous studies (Krebs et al., 2013; Krebs et al., 2010; Padmala & Pessoa 2011). Neurally, we hypothesized that the enhanced preparatory activity that we expected to observe in response to reward-prospect cues would be followed by attention-related modulations on the processing of the target Stroop stimuli, which would be reflected by larger N2 and P3 waves to those target stimuli. In addition, we anticipated that if advanced cuing of reward-prospect could indeed modulate the processing of stimulus conflict, then we would also see a reduction in the size or latency of the conflict-related negative deflection, the Ninc, and the associated subsequent late positive wave known as the LPC (Liotti et al., 2000).

Lastly, to further dissociate the processes involved in attention and reward-prospect, we looked at individual differences in these effects by examining between-subjects correlations of task performance with the associated neural activations. More specifically, we hypothesized that participants who were better able to utilize the reward-prospect information, as reflected by larger modulations of the cue-triggered preparatory activity with reward-prospect, would show greater facilitation of the Stroop stimulus processing and, in turn, greater reduction in conflict-related interference in the context of reward.

Method

Participants

Twenty-nine healthy volunteers (15 male and 14 female with a mean age of 22.4 [*SD*: 4.1] and 23.3 [*SD*: 3.9] years, respectively) participated in the study. All participants had intact color vision and normal or corrected-to-normal visual acuity.

Five participants were left-handed, while 24 were right-handed. One participant was excluded from the analysis due to excessive noise in the EEG data (i.e., over 50% of the EEG trials contained artifacts). All participants gave written informed consent as reviewed in accordance with protocols approved by the Duke Medical Center Institutional Review Board. Participants were paid \$15/h plus reward-associated bonuses accumulated over the experiment (mean bonus = \$18.5, $SD = 1.0$).

Apparatus

The task was programmed using the Presentation software package (version 14.1, <http://www.neurobs.com/>) for psychological experiment design. Stimuli were randomized using the R statistical programming software package (R Development Core Team, 2013). Stimuli were presented on a 60-Hz CRT monitor. Participants interacted with the Presentation software using a Logitech precision gamepad (<http://www.logitech.com/>). EEG was recorded using a 64-channel, custom-designed, extended-coverage Duke electrode cap (Electrocap, Inc., Eaton, OH) connected to a Neuroscan amplifier, using a right-mastoid reference during recording.

Task and stimuli

On all trials (see Fig. 1 for an overview), a cue stimulus (400-ms duration) was presented first. On 80% of the trials, the cue indicated that there would be either reward-prospect (40% of trials, indicated by a “\$”) or no-reward-prospect (40% of trials, indicated by an “&”) and was followed by a Stroop color–word stimulus, to which participants had to respond to the font color by pressing a prespecified button on the gamepad. These Stroop stimuli consisted of randomly

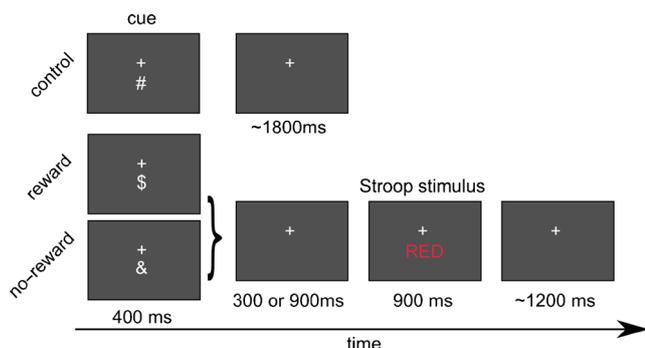


Fig. 1 Trial structure. Each trial started with a cue: “\$” for trials with reward-prospect, “&” for no-reward-prospect trials, and “#” for control trials. All cues were followed by a fixation cross and, in the reward-prospect and no-reward-prospect trials, by a Stroop stimulus to which participants needed to respond. Control cues indicated that no Stroop stimulus would follow and, thus, that there was no need to prepare for it. Note that in all the figures, “reward” and “no-reward” refer to the reward-prospect and no-reward-prospect conditions, respectively

selected color words (i.e., “RED,” “GREEN,” “BLUE,” and “YELLOW”), which were printed in the semantically corresponding font color on half of the trials (congruent targets) and in a different font color on the other half of the trials (incongruent targets). The other 20% of the trials were control trials, in which the cue (“#”) indicated that no target Stroop stimulus would follow and, thus, the participant did not need to prepare for it.

On the reward-prospect trials, participants could either gain 10 cents if they responded correctly and sufficiently quickly (see below for a description of criteria) or lose 10 cents if their response was incorrect or too slow. Participants were given feedback about their performance every 10 trials by a 2-s feedback screen containing the acquired monetary reward balance. In the no-reward-prospect trials, there was no gain or loss involved. In both the reward-prospect and no-reward-prospect conditions, the Stroop stimulus would follow at either a short stimulus interval (33% of the trials, SOA of 700 ms [400-ms cue duration + 300-ms fixation]) or a long stimulus interval (66% of the trials, SOA of 1,300 ms [400-ms cue duration + 900-ms fixation]). Intertrial intervals following the reward-prospect and no-reward-prospect trials, during which only a fixation cross was present, were varied between 1,000 and 1,400 ms. Intertrial intervals following control trials, during which only a fixation cross was present and no Stroop target word would occur or be expected, were varied between 1,600 and 2,000 ms.

To account for individual differences in RT and to keep all participants at a reward rate of approximately 70% (equivalent to a gain of around \$19 at the end of the experiment), a reward-related response window was set in which the participant needed to respond, with the upper bound of the response window being adjusted dynamically. More specifically, if the hit rate of the last 10 reward-prospect trials was lower or higher than 70%, 10 ms were either added or subtracted, respectively, to the response window. Note that these adjustments to the reward-eligible response window only affected the feedback for the participants and were not indicative of whether or not the trial was included in the behavioral and ERP analyses.

Procedure

Participants were positioned with their eyes 60 cm from the screen, which resulted in a visual angle of $\sim 1.5^\circ \times 5^\circ$ for the Stroop word stimuli. Participants were instructed to respond as quickly and accurately as possible. Behavioral responses were given with the index and middle fingers of both the left and right hands (counterbalanced), using a gamepad in which the front buttons were assigned to the four possible font colors. After task instructions, a short practice session followed (30 trials), which was repeated until participants achieved a hit rate of over 90% and in which the participants received

positive feedback on reward-prospect trials if they responded correctly and faster than 900 ms. The subsequent experimental session consisted of 11 blocks of 100 trials each. After each block, participants could take a break if they wished.

EEG recording and data analysis

For the compound-event trials (i.e., having a cue stimulus followed by a Stroop target stimulus), we used a design that had *reward* (reward-prospect vs. no-reward-prospect) and *congruency* of the Stroop stimulus (congruent vs. incongruent) as independent variables. In addition, for trial-to-trial variations of within-subjects task performance, we defined the factor *speed* (short-RT trials vs. long-RT trials), which was based on a median split within each condition and within each participant. Only reward-prospect and no-reward-prospect trials that had a long cue-to-Stroop-stimulus interval were included in the behavioral and ERP analysis (~140 trials for each condition), in order to be able to cleanly assess the cue-triggered activity in the cue–target interval. The short cue-to-Stroop-stimulus intervals were included to make sure that participants started preparation for the upcoming target as soon as the cue appeared onscreen. EEG recording was done with electrode impedances below 2 k Ω for the mastoids and ground electrodes below 5 k Ω for the remaining electrodes. All channels were recorded using an online high-pass filter of 0.01 Hz, a low-pass filter of 100 Hz, and a sampling rate of 500 Hz. Offline, the data was digitally filtered using a 30-Hz low-pass filter. Additional preprocessing included segmenting the data into time-locked epochs and rereferencing to the algebraically averaged mastoids.

The ERP analysis was based on 2,000-ms epochs (including 500 ms before event onset), locked to the onset of the cue for cue-related responses and to the onset of the target Stroop stimulus for the Stroop processing. Epochs containing eye blinks between 100-ms precue/pre-Stroop-stimulus and 200-ms postcue/post-Stroop-stimulus were rejected, thereby ensuring that participants were actually viewing the stimulus on a given trial. Outside of this window, eye blinks were corrected using independent components analysis. For each participant, trials on which multiple behavioral responses were recorded or where the behavioral responses were outside a 200- to 1,200-ms post-Stroop-stimulus response window or outside an interval of ± 2 SDs around the mean RT (for that participant and within each condition) were considered outliers and were excluded from the analysis. In addition, trials containing any remaining EEG artifacts (eye movements, muscle activity, drifts; approximately 10% of all data) and trials with incorrect behavioral responses were rejected from inclusion in the analyses. Fast and slow trials were also selectively averaged, using a median split (for each participant) of the RTs within each condition. ERP preprocessing

and analysis was performed using MATLAB (Release 2013) in combination with EEGlab (Delorme & Makeig, 2004) and Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). Time-frequency decomposition was performed using a Hanning taper window with a decreasing width for higher frequencies to control temporal smoothing (seven cycles per time window, resulting in a window of $1/\text{Hz} \times 7$ [e.g., for 12 Hz: $1/12 \times 7 = 580$ ms]) from 4 to 20 Hz in steps of 1 Hz, from 0.5 s precue to 1.5 s postcue in steps of 50 ms. (To accommodate the wider windows for lower frequencies, longer epochs were generated before performing time-frequency decomposition.) For the oscillatory power analyses, a baseline correction from 500 to 200 ms before cue onset was applied, yielding activity measures in units of decibel change, as compared with the baseline period.

Statistical analysis

The following regions of interest (ROIs) were defined: occipital, parietal, centro-parietal, central, fronto-central, and frontal. Intervals for measuring ERP components were defined by collapsing the ERPs over all conditions, using an orthogonal selection of interval for each component. For the cue-triggered ERPs, the occipital N1 component was defined as activity across the 140- to 180-ms postcue interval over the occipital ROI. The N2 component (negative occipitally and positive frontally) was calculated as a mean amplitude across the 200- to 300-ms interval over the occipital and frontal ROIs. The cue-triggered CNV activity was measured in the latter half of the cue–Stroop-stimulus interval (i.e., between 700 and 1,200 ms) in the fronto-central ROI (Grent-‘t-Jong & Woldorff, 2007). For the target-stimulus-locked ERPs, the N2 (also appearing as negative occipitally and positive frontally) was measured as the mean amplitude between 150 and 200 ms over the occipital and frontal ROIs. This interval was earlier, as compared with the latency found by Krebs et al. (2013), but because the topography as described in the Results section overlapped the topography found by Krebs et al. (2013), we will refer to this component as the N2. The P3 to the Stroop target stimuli was defined by a parietal ROI in the 300- to 600-ms post-Stroop-stimulus interval. However, the effect of reward-prospect on the target P3 was notably more anterior and started earlier, perhaps reflecting a P3a-like enhancement; for this reason, we also selected a frontal ROI for the P3 enhancement by reward-prospect in the 200- to 500-ms post-stimulus interval and report the statistics for both the frontal and parietal ROIs. For the conflict-related Ninc component, a centro-parietal ROI over 300–500 ms was used, and for the longer-latency LPC, a parietal ROI was used over a 700- to 900-ms poststimulus interval. For the oscillatory analyses, we used the fronto-central and occipital ROIs to match the CNV and occipital sensory ERP effects. We specifically focused on activity in the Alpha band (9–11 Hz). To make sure we would

optimally capture the Alpha effects to the cue, we defined a window from 500 to 1,200 ms post-cue-interval. Statistical analyses were done using the R statistical programming environment (R Development Core Team, 2013). Repeated measures ANOVAs (rANOVAs) were run on the behavioral and ERP/time-frequency effects. Effect sizes were reported for the rANOVA's, using the generalized η^2 (η_g^2 ; Bakeman, 2005). For correlations, the R^2 values are reported.

Results

Behavioral results

Participants responded more slowly to incongruent Stroop stimuli than to congruent ones (see Fig. 2 for RT values), $F(1, 27) = 142, p < .0001, \eta_g^2 = .11$, and had higher error rates (8% vs. 4%), $F(1, 27) = 25.0, p < .0001, \eta_g^2 = .12$. In addition, for Stroop stimuli cued by reward-prospect, participants responded faster, as compared with trials cued by no-reward-prospect (see Fig. 2), $F(1, 27) = 29.8, p < .0001, \eta_g^2 = .026$, and decreased error rates (5% vs. 7%), $F(1, 27) =$

11.8, $p = .002, \eta_g^2 = .023$. On the basis of previous studies, we expected participants to show reduced behavioral *interference* (incongruent minus congruent RTs) in the reward-prospect, as compared with the no-reward-prospect, condition. In contrast to this hypothesis, however, no reduction of interference was observed [congruency \times reward-prospect: $F(1, 27) = 0.27, n.s.$]. However, we did observe a large variability across participants in both the size of the interference reduction (mean = 2.43 ms, $SD = 24.9$ ms) and in the reward-prospect effect (reward-prospect minus no-reward-prospect; mean = 30.9 ms, $SD = 29.9$). Importantly, there was a robust correlation across participants between the interference effect and the reward-prospect effect, $R^2 = .27, p = .005$ (see also Fig. 2d), showing a relationship between the utilization of the advance information about reward-prospect and the degree to which participants were able to actually reduce interference in the reward-prospect condition. In addition, analysis of the standard deviations of the RT distributions revealed a decrease in the SDs in the reward-prospect, as compared with the no-reward-prospect, condition, $F(1, 27) = 15.6, p = .0005, \eta_g^2 = .020$. Similarly, the SD was decreased for congruent, as compared with incongruent, stimuli, $F(1, 27) = 35.0, p < .0001, \eta_g^2 = .078$. For the analysis of neural measures,

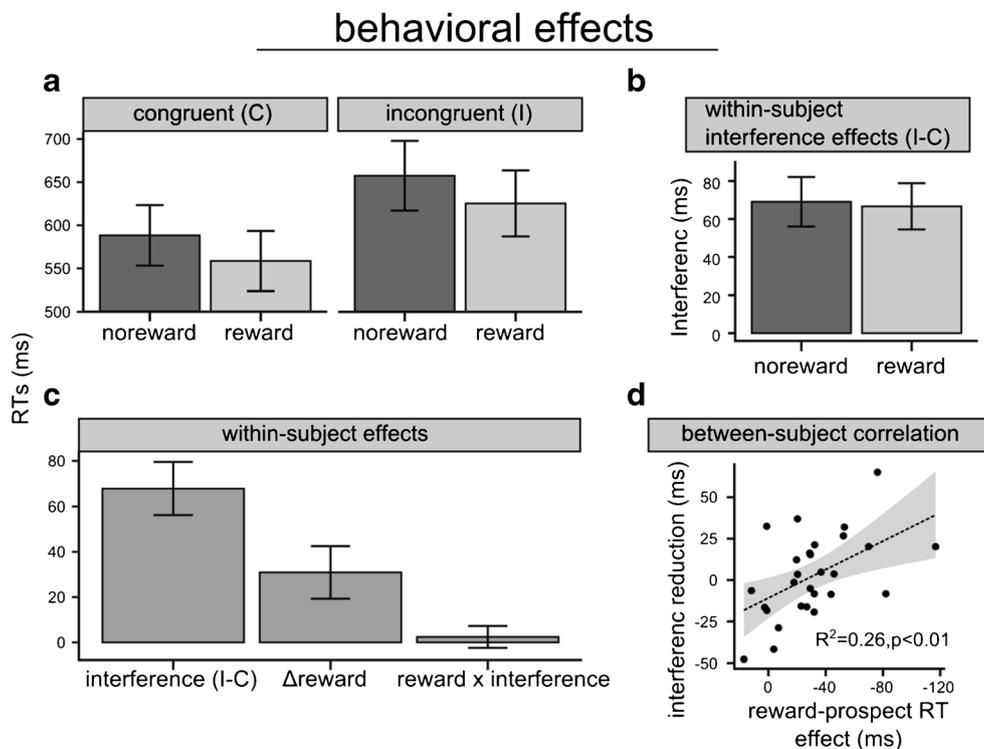


Fig. 2 Behavioral response time (RT) data. **a** The RT data averaged over the various conditions. **b** The within-subjects conflict-related interference effects (RTs for the incongruent trials minus the congruent ones), showing that these effects did not differ between the reward-prospect and no-reward-prospect conditions. **c** The RTs for the main effect of interference (incongruent minus congruent), the main effect of reward (reward-prospect minus no-reward-prospect) and the interaction of the two (reduction of interference as a function of reward), showing a main effect of

interference, a main effect of reward-prospect, but no interaction between the two. **d** The correlation across participants between the overall RT acceleration with reward-prospect (reward-prospect RT minus no-reward-prospect RT) and the reward-related reduction in behavioral interference (the more positive the value, the more the reduction in interference with reward). The plot shows that the greater the RT acceleration with reward, the greater the reward-related reduction in behavioral interference. Error bars represent standard error of the mean

we used a median split of RTs for the factor speed, which resulted in the following mean RTs ($\pm SD$): reward-prospect, short RTs, 517 ms (± 57); reward-prospect, long RTs, 693 ms (± 74); no-reward-prospect, short RTs, 539 ms (± 59); no-reward-prospect, long RTs, 731 ms (± 80) (median split was done separately for the congruent and incongruent conditions [using the mean], but is collapsed here).

ERP results

Cue-processing: effects of reward and speed

Cues that indicated reward-prospect, as compared with no-reward-prospect, elicited a larger occipital visual N1 around 150 ms [occipital ROI: $F(1, 27) = 11.18, p = .002, \eta_g^2 = .015$]. This occipital N1 enhancement with reward was followed at 250 ms by an enhanced occipital negativity, presumably an N2, $F(1, 27) = 21.2, p < .0001, \eta_g^2 = .013$, with similar scalp distributions as the N1 enhancement, but with the occipital negativity paired with a larger frontal positivity, $F(1, 27) = 19.0, p = .0002, \eta_g^2 = .017$ (cue-triggered ERPs are displayed in Fig. 3). This complex shows a similar topography as the occipital N2/frontal P2 complex reported by Krebs et al. (2013). In addition to an enhancing effect of reward on the frontal P2 positivity, there was also an interaction between speed and reward on the frontal ROI at this latency, $F(1, 27) = 8.9, p = .005, \eta_g^2 = .004$. Following the N2-latency modulations by reward, there was an effect on the parietal P3 (300–600 ms after cue onset) for both reward (larger for reward-prospect cues), $F(1, 27) = 11.8, p = .002, \eta_g^2 = .017$, and for the interaction between speed and reward, $F(1, 27) = 7.25, p = .012, \eta_g^2 = .003$. A similar enhancement of the P3 was observed when the cue was followed by a fast, as compared with a slow, behavioral response to the target, but only when cued by reward-prospect, as compared with no-reward-prospect, trials.

Between 600 and 1,300 ms after cue onset, ERPs elicited by both the no-reward-prospect and reward-prospect cues, relative to the control cues, showed a robust enhancement of the fronto-central negative-polarity wave characteristic of the hallmark CNV that is a marker for attentional preparatory activity (Luck, 2005). This CNV was largest for reward-prospect fast-RT trials and smallest for no-reward-prospect slow-RT trials. This relationship with RTs was most apparent in the later time range of the CNV (Fig. 3c). The reward-related CNV enhancement (reward-prospect minus no-reward-prospect) started as a negative deflection bilaterally over frontal and central sites and moved more posteriorly over time, similar to the CNV for the cued-reward and cued-no-reward trials, relative to the control cues, and similar to previous reports of cued attentional preparatory activity (Grentt-Jong & Woldorff, 2007). The relation between CNV size and behavioral RTs was particularly strong for no-reward-prospect

trials but mostly disappeared when reward-prospect was at stake. Statistical analyses of the CNV (measured from 700 until 1,200 ms with a fronto-central ROI) confirmed these effects—namely, a main effect of speed, $F(1, 27) = 6.25, p = .019, \eta_g^2 = .011$, a main effect of reward, $F(1, 27) = 22.1, p < .0001, \eta_g^2 = .10$, and an interaction between speed and reward, $F(1, 27) = 4.33, p = .047, \eta_g^2 = .005$.

The ERPs elicited by the Stroop target stimuli showed no differences with regard to the factors of reward or speed until 150 ms (Fig. 4). On trials with reward-prospect versus no-reward-prospect, target stimuli first elicited a larger frontal positivity in the 150- to 200-ms latency range, $F(1, 27) = 17.0, p = .0004, \eta_g^2 = .018$, which was paired with a simultaneous enhanced bilateral negativity over the occipital channels, $F(1, 27) = 4.7, p = .04, \eta_g^2 = .0024$. This effect has a similar topography as the occipital N2/frontal P2 complex reported by Krebs et al. (2013), as well as the N2/P2 elicited by the cue stimuli here, although the target-evoked N2/P2 occurred notably earlier, with a latency closer to the N1 to the cue. There was also an effect of speed (larger occipital N2 for shorter RT trials) and an interaction between reward and speed on the occipital N2 [speed, $F(1, 27) = 13.0, p = .0012, \eta_g^2 < .01$; speed \times reward, $F(1, 27) = 4.6, p = .04, \eta_g^2 < .01$], with the N2 being larger for rewarded fast trials, but the effect of N2 by speed was significant only in the no-reward condition. The interaction between speed and reward on the N2 effect was similar to the CNV enhancements, with the effect of speed being mostly absent in the reward-prospect condition.

The above effects of reward-prospect in the 150- to 200-ms time range were followed by an enhanced positivity in the P3 latency range [parietal ROI, $F(1, 27) = 9.6, p = .005, \eta_g^2 = .019$; frontal ROI, $F(1, 27) = 29.9, p < .0001, \eta_g^2 = .038$]. We also observed an effect of speed (larger for shorter RTs) on this component, as well as an interaction between speed and reward. The effect of speed on the P3 was larger in the reward-prospect condition than in the no-reward-prospect condition [speed: parietal ROI, $F(1, 27) = 71, p < .0001, \eta_g^2 = .09$; frontal ROI, $F(1, 27) = 37.7, p < .0001, \eta_g^2 = .054$; speed \times reward: parietal ROI, $F(1, 27) = 10.0, p = .004, \eta_g^2 = .0024$; frontal ROI, $F(1, 27) = 8.98, p = .006, \eta_g^2 = .003$], which was similar to the observed interaction with the P3 enhancement during the processing of the cue, but opposite in direction from the effect of speed \times reward on the CNV. Note that the reported F -values were extracted from both the parietal ROI and frontal ROI. The parietal ROI would be a typical topographical location of a P3 effect, while the topographic maps revealed the P3 effect of reward-prospect to be larger more anteriorly, where it started somewhat earlier, perhaps representing more of an enhancement of a P3a-like component.

The hallmark negative-polarity incongruity-related component (Ninc), as defined by comparing incongruent versus congruent target stimuli, $F(1, 27) = 28.3, p < .0001, \eta_g^2 = .018$, did not differ as a function of reward [Fig. 5; Ninc: congruency \times reward, $F(1, 27) = 0.11, p = \text{n.s.}$], paralleling the RT

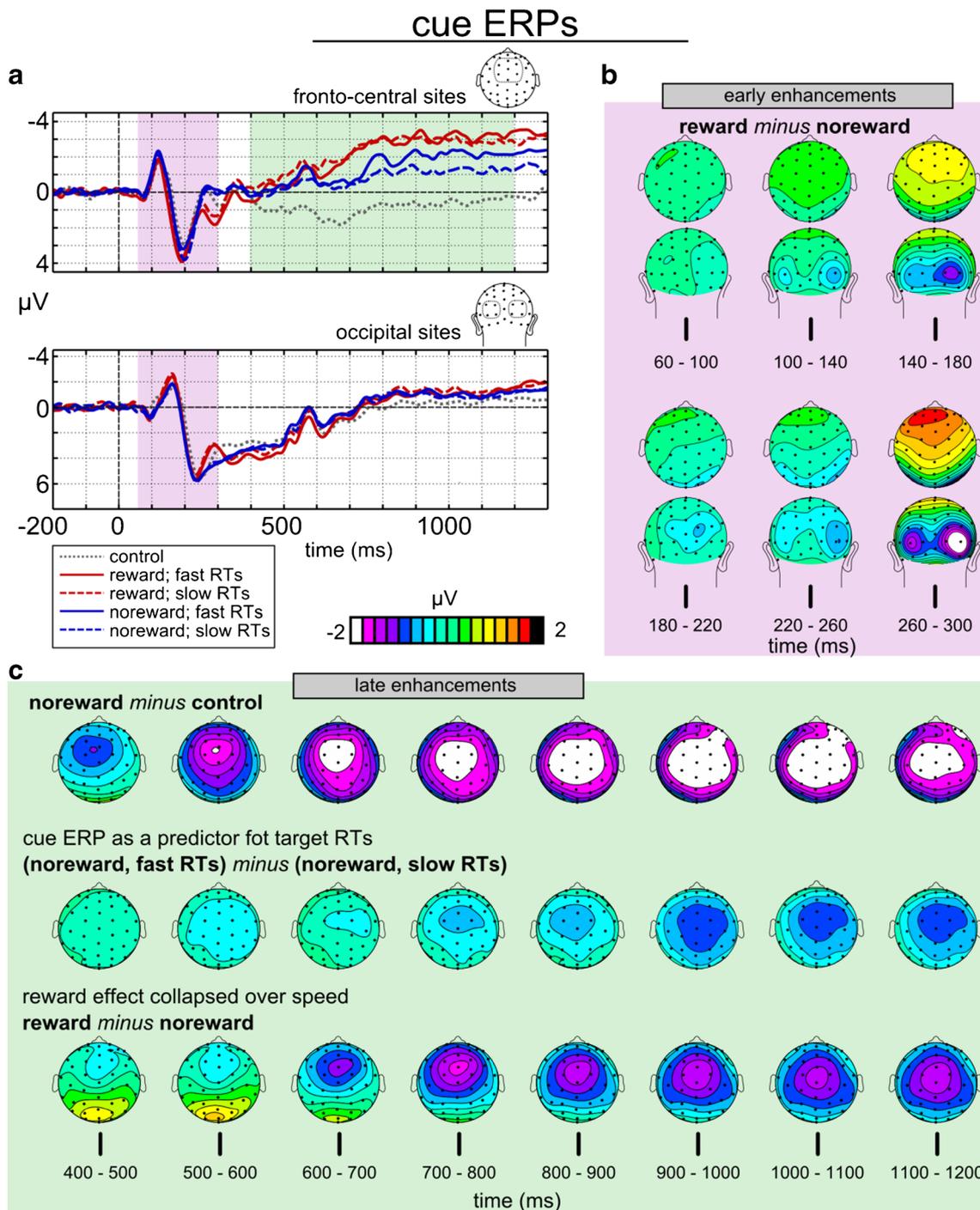


Fig. 3 Cue-elicited ERP effects. **a** The ERP waveforms for reward-prospect and no-reward-prospect, split out into cue-evoked ERPs which preceded “fast” response times (RTs) or “slow” RTs (median split) for the behavioral responses to the target. Effects of reward-prospect were observed on the occipital N1, N2, frontal P2, P3, and a fronto-central contingent negative variation (CNV) enhancement. The effect of speed was most pronounced on the CNV in the no-reward-prospect condition. **b** Topographic scalp maps of the “early” enhancement effects after cue onset showed the difference between ERPs evoked by reward-prospect cues minus no-reward-prospect cues. The topomaps reveal the effect of reward-prospect on the N1, N2, and P2. **c** Topomaps of the “late”

enhancements of the effect reward in response to the cue and speed as defined by the RTs on the subsequent target. The comparison between no-reward-prospect and control cues reveals a characteristic fronto-central negative wave (CNV). The comparison between short-RT and long-RT no-reward-prospect trials revealed that fast RT-trials were preceded by an enhanced negative fronto-central CNV deflection starting around 800 ms. The comparison between reward-prospect and no-reward-prospect cues showed a larger parietal P3 followed by a CNV enhancement for reward-prospect cues, as compared with no-reward-prospect cues, with a distribution similar to the speed effect. The CNV enhancement was also similar to the comparison of no-reward-prospect cues minus control cues

target ERPs

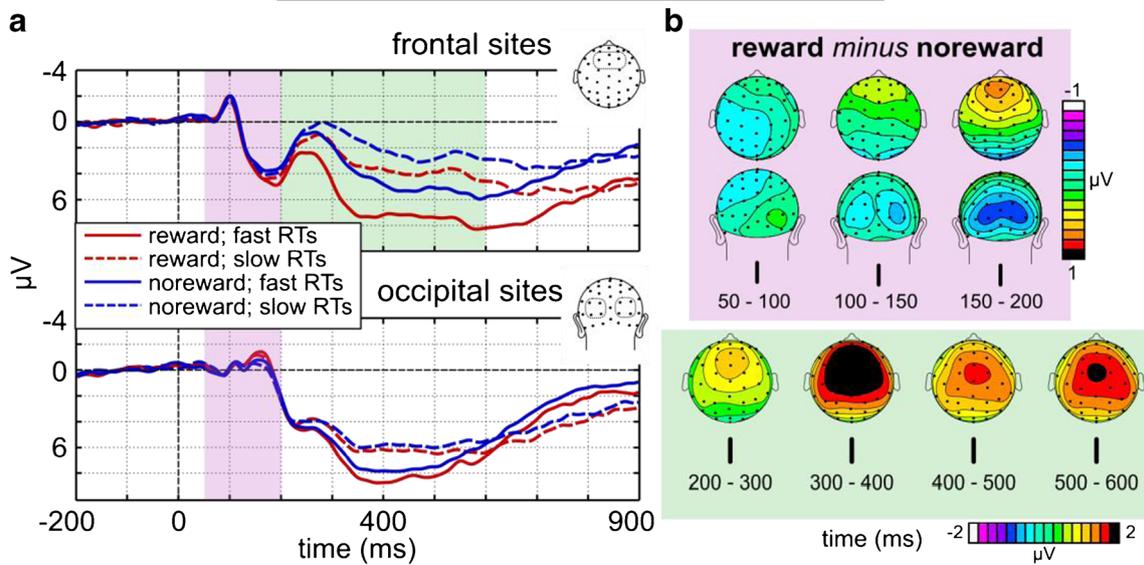


Fig. 4 ERPs elicited by the target stimuli, for short and long response time (RT) trials. **a** The ERPs elicited by reward-prospect and no-reward-prospect cues. There was an effect of reward-prospect on the occipital N2 and the temporally paired frontal positive P2, followed by an effect of both speed and reward-prospect on the P3. The dashed versus solid line ERPs indicate the potentials preceding short or long RTs by the

participants. **b** Topographic maps indicate the difference between potential reward and no-reward targets and illustrate the locations of the reward-prospect effect in the N2, P2, and P3 intervals. Note that the N2 is somewhat earlier, as compared with other studies, but has a similar topography as the N2 enhancement by reward as reported by Krebs et al. (2013)

pattern for these factors. In the same comparison, the Ninc was followed by a late positive component [LPC: $F(1,27) = 72.4$, $p < .0001$, $\eta_g^2 = .09$] in both the reward-prospect and no-reward-prospect conditions, again with no interaction between these factors [LPC: congruency \times reward, $F(1,27) = 0.65$, $p = n.s.$].

Correlation analyses

To investigate the relationship between the neural and behavioral effects of our manipulations, we defined two behavioral effects that were indicative of how participants used the reward-prospect information in order to examine how these

incongruity related target ERPs

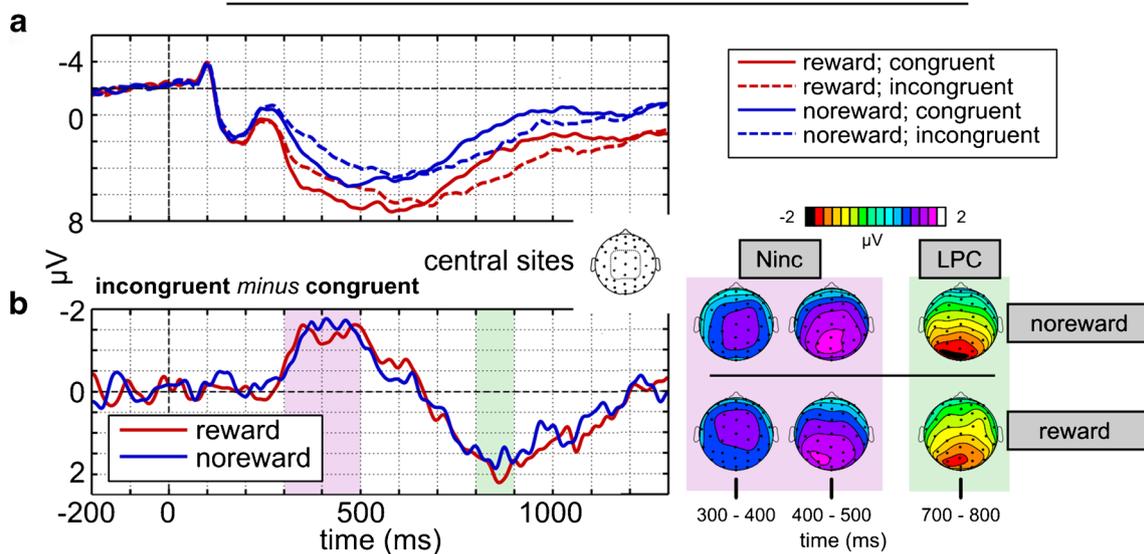


Fig. 5 Conflict-related ERP effects elicited by the target Stroop stimuli. **a** The ERPs for the reward and congruency conditions for the central region of interest. There was a clear hallmark conflict-processing marker, the central-parietal Ninc, followed by a parietal LPC. **b** The difference wave

between incongruent minus congruent Stroop stimuli for reward-prospect and no-reward-prospect. Scalp maps on the right illustrate that the Ninc and LPC do not differ between reward-prospect and no-reward-prospect trials

behavioral effects correlated with reward effects in the ERPs. For the first behavioral measurement of reward utilization, we used the overall acceleration of the RT with reward-prospect (reward-prospect minus no-reward-prospect). The second measure was the ability to minimize cognitive conflict as a function of reward (reduction of behavioral interference with reward-prospect, as compared with no-reward-prospect). Neural reward-prospect effects included the enhancements to the cue- and target-elicited responses described above, as well as the conflict-related Ninc and LPC. The neural-behavioral correlations are summarized in Fig. 6.

The correlation analyses showed a close relationship across participants between the sizes of neural reward-related enhancements and the two behavioral markers of reward utilization. First, the behavioral RT acceleration correlated with the reward-related enhancements of both the cue-triggered CNV (Fig. 6a) and the target-triggered frontal P3 enhancement (Fig. 6b) with reward-prospect ($R^2 = .24$, $p = .008$; parietal ROI, $R^2 = .24$, $p = .009$; frontal ROI, $R^2 = .28$,

$p = .004$). Moreover, these two neural effects of reward-prospect were correlated with each other (parietal ROI, $R^2 = .34$, $p = .001$; frontal ROI, $R^2 = .65$, $p < .0001$); that is, the larger the reward-prospect effect on the cue CNV, the larger the target P3 enhancement with reward-prospect (and the greater the RT acceleration). As was mentioned above, participants showed no overall reduction of interference, measured behaviorally or neurally, on reward-prospect trials. In contrast, across participants, there was a neural-behavior relationship between the reward-related reduction of behavioral interference and the CNV and target-related P3 enhancement by reward-prospect, with participants who elicited larger cue-triggered CNV and frontal target P3 modulations by reward-prospect also showing reduced behavioral interference with reward-prospect ($R^2 = .28$, $p = .004$; parietal ROI, $R^2 = .16$, $p = .035$; frontal ROI, $R^2 = .20$, $p = .017$). It is noteworthy that between-subjects behavioral variance was not correlated with earlier-latency enhancements in either the cue (N1) and target (N1 and N2) ERPs by reward-prospect.

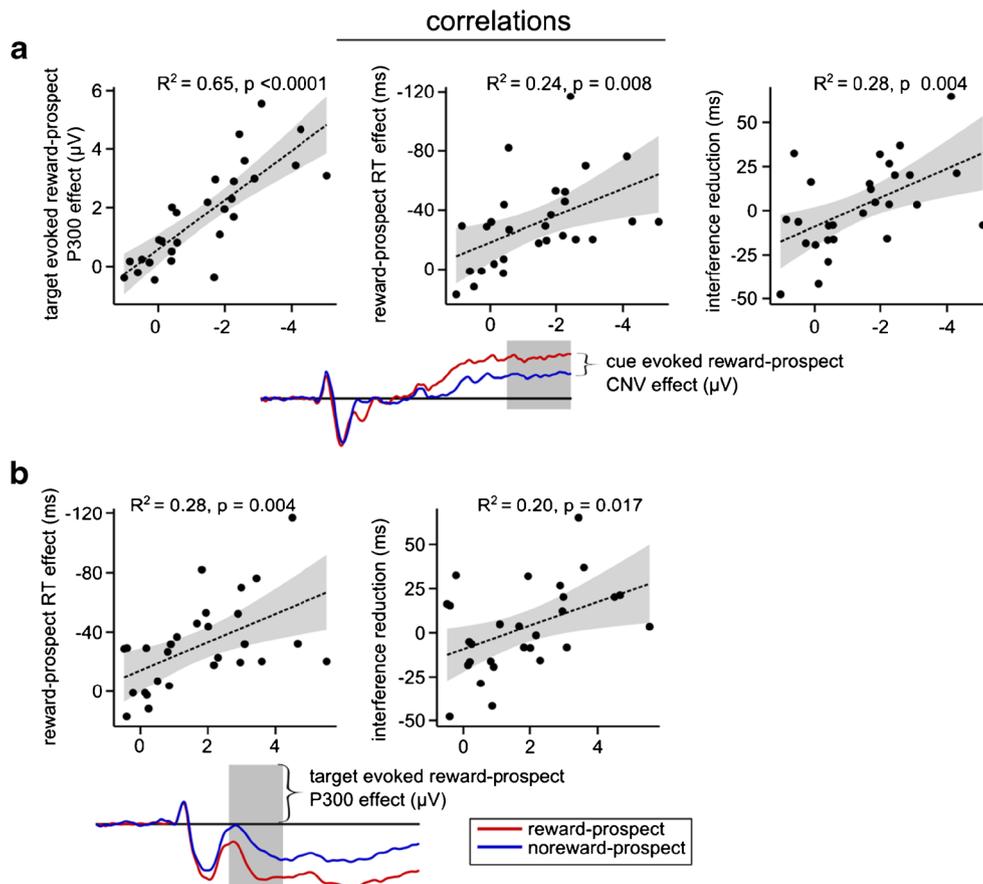


Fig. 6 Correlations between behavior and the cue and target ERPs. Between-subjects correlations were based on the mean response times (RTs) of the reward-prospect effect, the reduction in the conflict-related interference effect, the neural mean amplitudes of the cue-evoked reward effect on the fronto-central contingent negative variation (CNV; 700–1,200 ms), and the target-evoked reward effect on the frontal P3 (200–500 ms). **a** Left plot: correlation between the cue-evoked CNV (x-axis)

and the target-evoked frontal P3 (y-axis). Middle and right plots show the correlations between the reward effect on the cue CNV (x-axis) and the reward effects on the overall RTs and on the behavioral interference effect, respectively (y-axis). **b** Correlation between the P3 component of the target-evoked ERPs (x-axis) and behavioral markers for reward utilization (y-axis). Fitted lines are based on a linear model fit, and shaded areas show a 95% confidence interval for the fitted line

Effect of reward-prospect on cue-evoked oscillatory Alpha activity

To look at effects on time-locked oscillatory Alpha activity, two ROIs (fronto-central and occipital) were used (for an overview of the time-frequency results, see Fig. 7). Inspection of the spectra (Fig. 7a) revealed a power increase in the low-Alpha-band range (7–9 Hz) over the latency of 100–300 ms after cue onset in the occipital ROI for reward-prospect cues, as compared with no-reward-prospect ones [occipital: $F(1,27) = 8.82$, $p = .0044$, $\eta_g^2 = .02$]. This effect may be largely due to an enhancement of the occipital N2 (correlation: $R^2 = .41$, $p = .0003$). In the Alpha-band (9–11 Hz), during the period of the CNV (500–1,200 ms), participants showed an effect of both speed and reward in the occipital channels [reward, $F(1,27) = 19.9$, $p = .0002$, $\eta_g^2 = .09$; speed, $F(1,27) = 12.2$, $p = .0016$, $\eta_g^2 = .016$]. In the fronto-central channels, there was an effect in

Alpha for speed (more reduction of Alpha for faster trials) and for reward (more reduction for reward-prospect trials) and an interaction between the two [reward, $F(1,27) = 9.7$, $p = .0043$, $\eta_g^2 = .07$; speed, $F(1,27) = 5.05$, $p = .033$, $\eta_g^2 = .009$; speed \times reward, $F(1,27) = 4.9$, $p = .036$, $\eta_g^2 = .01$]. Interestingly, this interaction followed the opposite pattern than that of the CNV (Fig. 8). More specifically, fronto-central Alpha showed a large difference between long and short RT trials for the reward-prospect condition and very little difference in the no-reward-prospect condition. This is in sharp contrast to the fronto-central CNV pattern (described above), in which the long and short RT trials showed a large difference in the no-reward-prospect condition and little in the reward-prospect condition. After normalization to control for differences between the Alpha and CNV units, this differential interaction pattern was confirmed by a significant three-way interaction [speed \times reward \times neural measure, $F(1,27) = 9.2$, $p = .0053$, $\eta_g^2 = .08$].

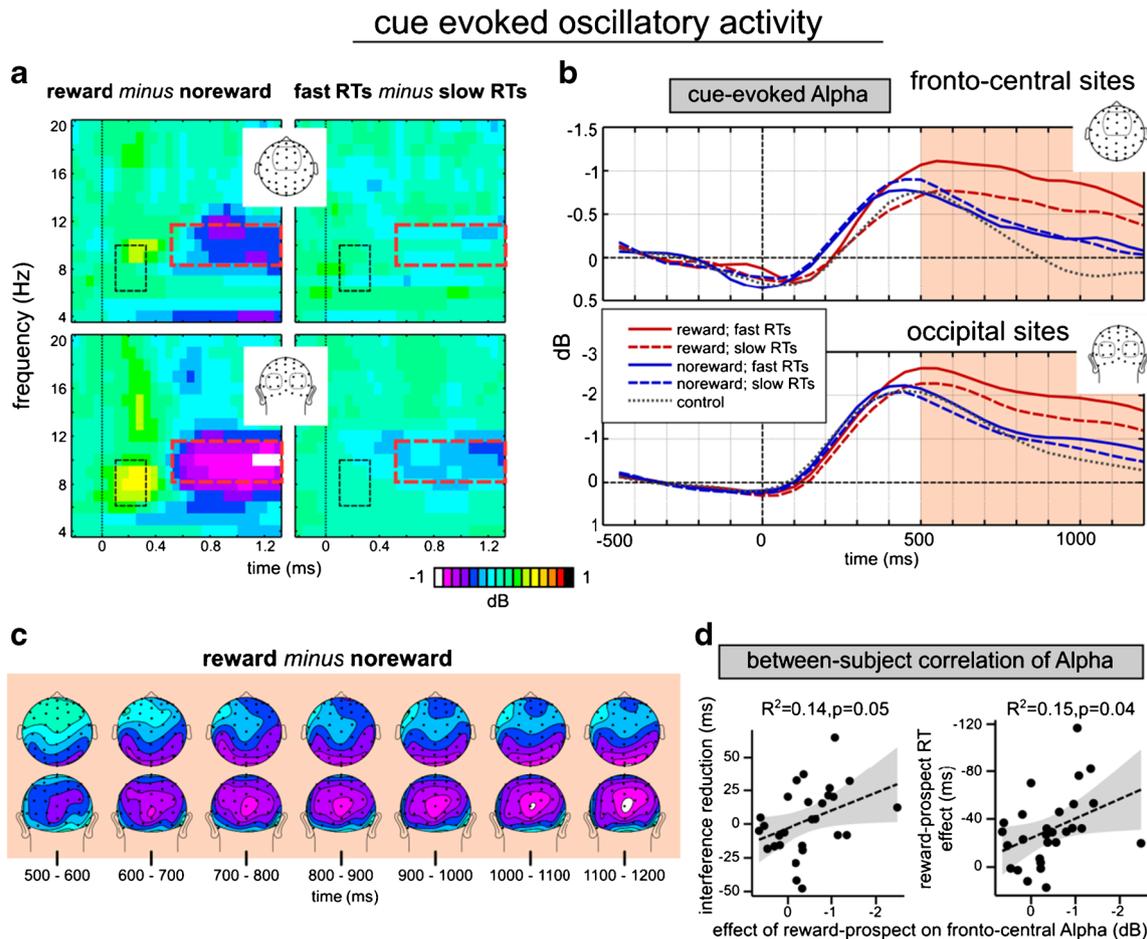


Fig. 7 Effects on oscillatory EEG activity. **a** The spectrograms illustrate the effect of reward-prospect and within-subjects task performance (short response times [RTs] versus long RTs) for different frequencies and time. Note that the effect of oscillatory Alpha for reward is substantially larger than that for speed. **b** Traces reflect oscillatory Alpha for their respective

region of interest and condition. **c** The scalp distribution of Alpha that was largest over the occipital channels. **d** Plots showing significant correlations between reward utilization measures (reward-prospect RT effect and reduced interference) and fronto-central Alpha

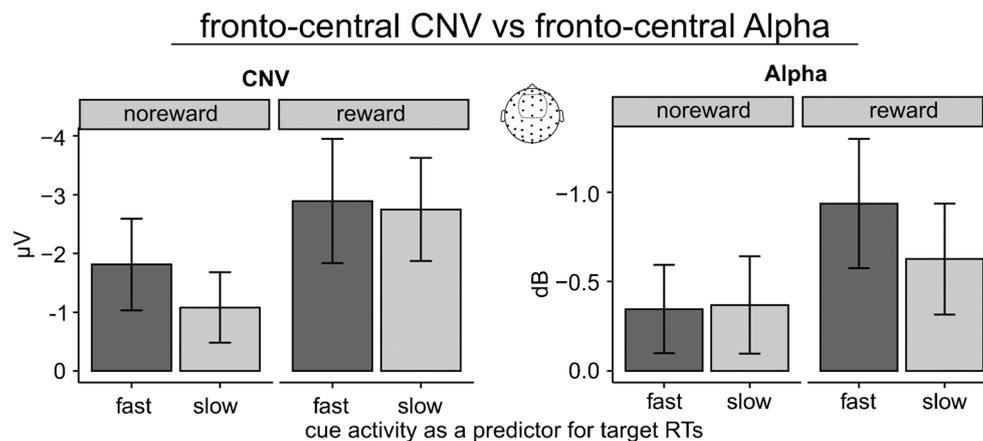


Fig. 8 Differential reward \times speed interactions for the contingent negative variation (CNV) and Alpha. Cue-evoked oscillatory Alpha and CNV activity showed differential patterns with respect to the effect of reward-

prospect and within-subjects task performance. Error bars reflect the standard error of the mean

Modulations of the cue-triggered occipital Alpha did not correlate across-subjects with the reward-prospect RT effect, $R^2 = .10$, $p = .10$, but data inspection revealed a particularly strong outlier with regard to the occipital Alpha reductions by reward-prospect, as compared with no-reward-prospect (mean, -0.76 dB, SD , 0.91 dB; outlier value, -4.6 dB). We thus ran a form of robust regression known as an M-estimation linear model, which revealed a relationship of occipital Alpha with reward-prospect, $t(27) = 3.21$, $p = .004$. No relationship was found between interference reduction and occipital Alpha, $R^2 = .11$, $p = .09$. Within the fronto-central ROI, Alpha reductions correlated with both the reward-prospect RT effect and reduced interference, $R^2 = .15$, $p = .039$, and $R^2 = .14$, $p = 0.046$, respectively (see also Fig. 7), as well as with enhanced CNV size, $R^2 = .18$, $p = .027$. Specifically, the larger the CNV enhancement, the more the decrease in Alpha.

Discussion

Summary

The overarching goal of the present study was to gain insight into the neural mechanisms by which reward-prospect and attentional control interact, in the context of a task requiring processing of conflicting stimulus inputs. We recorded electrical brain activity during a cued-reward Stroop paradigm, in which we specified three attention-related within-subjects factors of interest: attentionally prepare versus not-prepare, reward-prospect versus no-reward-prospect, and trial-to-trial variations in attention as reflected by slow and fast responses to the subsequent Stroop stimulus. We also looked at how the effects of reward-prospect on preparatory brain activity ramified into task performance on the Stroop stimulus. The results indicate a number of key findings. Behaviorally, participants

responded faster when cued with reward-prospect, as compared with no-reward-prospect. Neurally, we saw several effects on the cue-triggered activity. (1) There were effects of attentional preparation, reward-prospect, and within-subjects task performance on both the CNV and the pretarget oscillatory Alpha. (2) Reward-related CNV increases and Alpha decreases within subjects ramified into shorter overall RTs, but not into reductions in either the behavioral or neural markers of conflict processing. (3) Across participants, however, reward-related CNV increases and Alpha decreases correlated positively both with overall RT acceleration and with conflict-effect reduction. Interpretation and implications of these results are discussed below.

Reward-predicting cues triggered enhanced early-latency neural activity

Cue stimuli that signaled the prospect of reward induced several relatively early-latency effects on the sensory ERPs to those cues – in particular, enhancements of ERP components in the 100–300 ms range. Most novel in this regard was an enhancement of the cue-triggered N1 component over visual cortices. Modulations of the N1 amplitude have been associated with different forms of selective attention (Hillyard & Anllo-Vento, 1998; Mangun & Hillyard, 1991), suggesting that the observed N1 enhancement likely reflects enhanced sensory processing of the reward-predicting cue due to its greater saliency (see also Hickey et al., 2010; Hickey & Zoet, 2012). Subsequently, we observed a reward-related enhancement of the occipital N2 component, which had a similar distribution as the early N1 but was paired with a frontal positivity (similar effects were observed by Krebs et al., 2013). N2 amplitude enhancements have been associated with the orientation of attention toward information that is relevant, such as relevant pop-outs in a visual search array

(Luck & Ford, 1998) or stimuli associated with reward (Schupp, Flaisch, Stockburger, & Junghöfer, 2006). In line with these findings, the enhancement of the N2 would appear to reflect the relevance of reward-prospect and the related increase in attention toward the further processing of this information. In other words, after identifying that a cue predicted reward-prospect (N1), participants seem to allocate more attention toward that reward-predicting stimulus (N2).

Particularly striking in the present results was a robust boosting of the CNV with reward-prospect in the later period of the cue–stimulus interval. This CNV boosting started anteriorly and moved more posteriorly with time. This frontal-to-parietal topographic shift is in line with previous literature on top-down attentional control in the fronto-parietal attentional network (Buschman & Miller, 2007; Grent-‘t-Jong & Woldorff, 2007; Nagai et al., 2004). Moreover, we have recently observed a similar enhancement of the CNV in response to reward-prospect cues in an attentional cuing paradigm (Schevernels, Krebs, Santens, Woldorff, & Boehler, 2014). With regard to the underlying neural generators of this reward-elicited CNV modulation, it is worth considering the results of a previous study that employed a cued rewarded Stroop task similar to the present one but while recording fMRI (Padmala & Pessoa, 2011). Specifically, the authors found enhanced neural activity for reward-prospect cues, as compared with no-reward-prospect cues, in a network of fronto-parietal attentional control regions, which have been closely associated with the generation of the CNV (Grent-‘t-Jong & Woldorff, 2007).

The noticeable CNV increase by reward-prospect, on top of the increased CNV by the active preparation (control cue vs. no-reward-prospect), along with variations due to within-subjects task performance (short vs. long RTs) is consistent with the interpretation that a key way by which the reward-prospect influences behavior is by marshalling top-down attentional resources toward the goal of enhancing performance. This is further supported by the large increase in the CNV, with reward-prospect being paralleled by an improvement in task performance for the target Stroop stimuli that followed (i.e., shorter RTs and higher accuracy). These findings are consistent with those of previous studies (e.g., Haagh & Brunia, 1985; Hillyard, 1969) showing that CNV size is generally predictive of RTs, supporting the view that the more effective participants are in preparing their attentional system for an upcoming target stimulus, the shorter the RTs to that target (see also Weissman et al., 2006). Interestingly, in the present study, we observed a within-subjects interaction effect of reward-prospect and within-subjects task performance (as reflected by differences between trials with short and long RTs) on the CNV size. In particular, the large CNV elicited by the reward-prospect cues did not vary as a function of long versus short RTs to the targets for those trials, whereas in the no-reward-prospect condition, the CNV difference was substantially enhanced for short versus long RTs, with a

distribution similar to the CNV attentional-preparation effect and that of previous attention-related enhancements of the CNV. This pattern suggests that the CNV in the reward-prospect condition may have been essentially “maxed out” and that the RT variations in the responses to the later target stimuli derived from a different processing variability. Notably, the CNV variations did not linearly predict RTs, since the fastest no-reward-prospect trials were substantially faster, as compared with the slowest reward-prospect trials, suggesting that a larger CNV does not in and of itself necessarily result in shorter RTs; that is, the CNV does not seem to be the only factor that determines subsequent behavior. Trial-to-trial variations in attentional preparation in the no-reward-prospect condition, in which the attentional preparation was presumably not maxed out, as reflected by larger CNV variation, may have more directly ramified to the later RT effects. Consistent with this differential preparatory pattern and a possible ceiling effect for the CNV for reward trials is that the standard deviation of the RTs was significantly lower in the reward-prospect, relative to the no-reward-prospect, condition.

Preparation processes elicited by the cue were also reflected in oscillatory brain activity. Participants showed increases in low-Alpha-band activity with reward-prospect, as compared with no-reward-prospect, during the early phase (100–300 ms after cue onset) of the cue–stimulus interval. This low-Alpha-band effect may be related to the observed N2 enhancements, as reflected by the high correlation between the two measures. At longer latencies (500–1,200 ms) in response to reward-prospect cues, there were particularly strong decreases in Alpha power. Such decreases in Alpha power are generally considered to also be a hallmark neural-activity marker for increased attention (Worden et al., 2000).

Our within-subjects task performance data provide interesting suggestions for differential roles for preparatory Alpha and preparatory CNV activity. In particular, we observed dissociation between the effects on these two cue-elicited neural markers for preparatory attention with regard to the interactions of reward-prospect and RT speed (short vs. long RTs). As was noted above, the large CNV elicited by the reward-prospect cues did not vary as a function of response speed to the targets in these trials, suggesting that preparatory activation reflected by the CNV might have been maxed out in this condition. In the no-reward-prospect condition, where lower CNVs were observed, the CNVs were substantially larger for short versus long RTs. We also found greater decreases in fronto-central Alpha power for reward-prospect versus no-reward-prospect conditions, consistent with increased preparatory attention. The interaction of reward-prospect with RT speed for the alpha decreases, however, differed relative to the pattern seen for the CNV—namely, that a robust power reduction was observed for short versus long RT trials in the reward condition (more reduction for short RTs)—but did not

differ in the no-reward-prospect condition. This differential pattern of results suggests that different preparatory mechanisms are reflected by the Alpha and CNV modulations. It might be hypothesized that Alpha modulations are more closely related to suppression of irrelevant information (e.g., Bazanova & Vernon, 2013; Geerligs, Saliassi, Maurits, & Lorist, 2012; Klimesch, Sausen, & Hanslmayr, 2007) or perhaps to the task-set mapping (e.g., Grent-‘t-Jong et al., 2011), rather than to selective attention or more general effects as indexed by the CNV. Future studies will be necessary to delineate the functional relationships between these two neural markers for attention-related preparatory processes and their marshalling by reward-prospect.

Reward-prospect resulted in enhanced target stimulus processing

Following the preparatory effects in the cue–stimulus interval, we observed an enhanced N2 in response to the Stroop target stimulus when there was the prospect of reward. A similar effect was observed by Krebs et al. (2013) in response to Stroop stimuli whose font color was associated with reward (rather than the prospect of reward being cued from trial to trial, as was done here). However, the N2 component described by Krebs et al. (2013) was later compared with the N2 found here, which may be due to the effect of cuing in the present study. The enhanced N2 for both the cue and the target seems likely to reflect the orientation of attention toward a stimulus with reward possibilities. Notably, this measure was not correlated with behavioral improvements in reward utilization across participants, which supports the view that the occipital N2 enhancements are related to an attentional/salience-related enhancement of an identification process, which does not necessarily have consequences for the actual improvement of performance due to utilization of reward-prospect occurring in a later stage. With respect to the target, this enhanced N2 also indicates that participants were able to rapidly boost early processing of relevant information if they were cued with reward information. The early occipital brain activity was again paired with a frontal positivity and was followed by a notably more frontal P3 wave, perhaps a P3a-like component (Luck, 2005; Luck & Kappenman, 2011; Polich, 2007), which would appear to reflect the reward-related boosting to improve processing of the target (Goldstein et al., 2006; Krebs et al., 2013; Marini, Marzi, & Viggiano, 2011; Y. Wu & Zhou, 2009).

Utilization of cued reward-prospect information improves target stimulus processing

In the present data set, we observed large individual differences in the degree and nature of the improvement of performance with reward-prospect. Those participants showing

large improvements in behavioral performance with reward-prospect also showed more pronounced modulations of neural activity patterns. Most important, we observed a robust relationship across participants between CNV enhancement and the behavioral RT effect (larger reward-related CNVs correlated with greater reward-related acceleration of the RTs), showing that the enhanced CNV activation was predictive of behavioral performance. The same across-participants relationship held for the reductions of the fronto-central Alpha activity, which also correlated with the CNV enhancements. Modulations of the N1/N2 components elicited by target Stroop stimuli did not appear to predict performance across participants, however, indicating that these relative early ERP components more likely reflect the detection of reward-prospect (reflecting enhanced saliency), rather than being a marker for actual utilization of that reward-prospect information. In other words, people who were less sensitive to reward-prospect still appeared to identify the information as effectively as the reward-sensitive group, but they did not necessarily utilize this information as effectively for optimizing future information processing.

Increased utilization of reward-prospect information reduces behavioral interference

One of our initial hypotheses was that cued reward-prospect, with its expected marshalling of preparatory attentional resources, would reduce stimulus conflict effects. Behaviorally, we expected that as a result the RT difference between incongruent and congruent Stroop words would become smaller in the reward-prospect condition, as compared with the no-reward-prospect condition. Although we did not find this interaction between reward-prospect and the amount of behavioral interference, we did observe that the amount of reward-related reductions in behavioral interference was correlated (across participants) with the overall reward-prospect effect of shorter RTs, the enhanced cue-triggered CNVs, the degree of reduction of cue-triggered fronto-central Alpha, and the size of the target-triggered P3. Notably, no correlation was found between the conflict-related Ninc or LPC components and the reduction of interference by reward-prospect. In other words, these findings imply that conflict-related processes underlying the Ninc and the LPC are not sensitive to reward-prospect when that prospect is cued ahead of time, at least for the conflict-inducing stimuli employed here. These findings indicate that the reduction of interference across participants was more likely related to the effectiveness of the utilization of the reward-prospect information and to the corresponding changes in neural preparation and subsequent target processing than to an earlier or more efficient processing of conflict (Ninc and LPC).

In contrast to the between-subjects correlations, we did not find an overall effect of cued reward-prospect on conflict-related interference, measured either behaviorally or neurally.

This would seem to be in disagreement with several previous studies that have reported main effects of reward on conflict processing (Krebs et al., 2013; Krebs et al., 2010; Padmala & Pessoa, 2011). There are several possible reasons for this discrepancy. First, it is important to distinguish between paradigms (and behavioral circumstances) that entail cued-reward or *reward anticipation* (e.g., the present study and Padmala & Pessoa, 2011) and ones that entail *reward association* of certain target stimuli or features (e.g., the Krebs et al. studies). Reward anticipation, such as was used here, is induced by cuing the participant on each trial as to whether there would or would not be the prospect of reward on that trial. In such a circumstance, a reduction of conflict interference requires that the reward anticipation (and any attentional variation it might induce) leads to activation of a top-down preparatory mechanism that either enhances the processing of the relevant features of the target that follows or suppresses the processing of its irrelevant, conflicting features (or both). If, however, the preparatory processes lead to an overall enhancement of the processing of the target stimulus (that is, of *all* its features), it will not necessarily reduce conflict processing, because the processing of both the relevant and conflicting task-irrelevant features will be enhanced. In a reward-association conflict paradigm, on the other hand, such as in the Krebs et al. (2013, 2010) studies, there is no cuing. Rather, a specific feature of the target stimulus is associated with reward during the whole session. In this circumstance, the processing of reward-associated relevant features will tend to be selectively boosted in a more bottom-up manner, due to their acquired saliency from the reward association, relative to the processing of the irrelevant features. This selective enhancement of processing would then tend to reduce the behavioral costs related to conflict processing on incongruent trials. This distinction between reward cuing and reward association is thus an important one to make, given that they may well invoke different mechanisms by which reward can influence processing, which might explain why conflict reduction effects would be more likely observed in the association paradigms.

On the basis of the above considerations, it is important to also discuss why the results differ between the present study and Padmala and Pessoa (2011), since both employed a trial-by-trial cuing approach in a Stroop-like task. A possible explanation may derive from key differences in the specific Stroop tasks and stimuli that were employed and, moreover, may be related to the selectivity hypothesis detailed above. More specifically, in our study, we used classic Stroop words, with color words in different font colors that were either congruent or incongruent. In such a paradigm, the relevant feature (i.e., the font color) is fully integrated into the same object with the irrelevant feature (i.e., the word meaning). In contrast, Padmala and Pessoa used pictures overlaid with words that were either congruent or incongruent, and thus

the relevant and irrelevant stimuli were separate (and perhaps more separable) objects. Accordingly, we speculate that in the reward-cuing condition in the Padmala and Pessoa study, participants were able to more selectively filter out the irrelevant stimuli and focus more on the relevant one, whereas in our study, it was more difficult to selectively filter out the irrelevant feature from the relevant one, since they were integrated into the same object.

Furthermore, but perhaps more speculatively, it is possible that the inconsistent findings between these studies are due to differences in intrinsic motivation. Multiple studies have shown that an extrinsic reward can undermine intrinsic motivation (for a review, see Deci, Koestner, & Ryan, 1999). Specifically, high, as compared with low, levels of intrinsic motivation may result in higher levels of accuracy and a diminished effect of extrinsic reward. Indeed, studies that reported reduced interference in reward conditions (Krebs et al., 2013; Krebs et al., 2010; Padmala & Pessoa, 2010) also reported substantially lower accuracy for incongruent no-reward-prospect trials, as compared with rewarded ones (differences ~8%). In contrast, the studies that did not report reduced interference in reward trials (the present study and Krebs et al., 2011) showed only a marginal reduction in accuracy (~2%). Thus, the individual level of intrinsic motivation may be another important factor to consider in studies investigating reward processing (Wu, Samanez-Larkin, Katovich, & Knutson, 2014). More generally, future research will be needed to verify the exact conditions under which a reward-related reduction of interference will occur.

As was noted above, although we did not find a main effect of conflict reduction, we did find an across-participants correlation indicating that the more the participants utilized the reward-prospect information, measured both neurally and behaviorally, the more reduction there was in conflict-induced costs. Thus, this may reflect a strategy or ability difference between the participants, in that some of them may be able to use the advance cuing information effectively to selectively enhance relevant features or suppress irrelevant features in the same object. In contrast, it is possible that other individuals use the reward-prospect mainly to enhance processing of the entire target stimulus input, including all its features. In the latter group of individuals, reward-prospect would not be expected to lead to interference reduction and could possibly even lead to greater conflict.

Conclusions

By using a cue to inform the participant about the reward-prospect on each trial, the present experiment provides a mapping for the cascade of neural processes underlying the utilization of reward information. Key results include that reward-prospect resulted in enhancement of neural markers

reflecting attentional preparation and target stimulus processing, as well as in an overall acceleration of behavioral responses. In addition, across participants, the degree of preparatory attentional processes with reward-prospect (as measured by enhancements of their preparatory CNV activity and reductions in their Alpha-band activity) correlated with the reduction of behavioral measures of conflict. Together, these findings suggest that the utilization of reward-prospect information provided by a cue stimulus results in specific enhancement of attentional-control processes used to improve stimulus processing and the reduction of stimulus conflict.

Author Note This work was supported by grants from the National Institute of Mental Health (R01-MH060415) and the National Institute of Neurological Disorders and Stroke (R01-NS051048) to M.G.W.

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