



Research report

Long-lasting effects of performance-contingent unconscious and conscious reward incentives during cued task-switching

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ABSTRACT

Motivation is often thought to interact consciously with executive control, although recent studies have indicated that motivation can also be unconscious. To date, however, the effects of unconscious motivation on high-order executive control functions have not been explored. Only a few studies using subliminal stimuli (i.e., those not related to motivation, such as an arrow to prime a response) have reported short-lived effects on high-order executive control functions. Here, building on research on unconscious motivation, in which a behavior of perseverance is induced to attain a goal, we hypothesized that subliminal motivation can have long-lasting effects on executive control processes. We investigated the impact of unconscious/conscious monetary reward incentives on evoked potentials and neural activity dynamics during cued task-switching performance. Participants performed long runs of task-switching. At the beginning of each run, a reward (50 cents or 1 cent) was displayed, either subliminally or supraliminally. Participants earned the reward contingent upon their correct responses to each trial of the run. A higher percentage of runs was achieved with higher (conscious and unconscious) than lower rewards, indicating that unconscious high rewards have long-lasting behavioral effects. Event-related potential (ERP) results indicated that unconscious and conscious rewards influenced preparatory effort in task preparation, as suggested by a greater fronto-central contingent negative variation (CNV) starting at cue-onset. However, a greater parietal P3 associated with better reaction times (RTs) was observed only under conditions of conscious high reward, suggesting a larger amount of working memory invested during task performance. Together, these results indicate that unconscious and conscious motivations are similar at early stages of task-switching preparation but differ during task performance.

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1. Introduction

1.1. Unconscious motivation and executive control

We generally believe that we decide what to do and that we consciously control our behavior. Our behaviors seem to originate in our conscious decisions to pursue desired goals. Considerable research, however, has demonstrated that our brains and behavior are strongly influenced by unconscious motivational factors (Custers and Aarts, 2010; Dijksterhuis and Aarts, 2010; Hassin et al., 2005; Libet, 2004; Wegner, 2002). One of the most important conscious motivational factors may be to earn money, since money is ubiquitous in daily life and people perform better when money is at stake. But will a person maintain the same level of motivation when he or she is unaware of the reward? An elegant empirical proof was provided by Pessiglione et al. (2007), who invited participants to perform a task in which they could earn money by squeezing a handgrip. Before each squeeze, the money that could be earned was subliminally or supraliminally displayed. Regardless of whether participants could or could not report how much money was at stake, they deployed more force for higher amounts. Moreover, a specific basal forebrain region was involved in both subliminal and supraliminal rewards.

Subsequent studies have reported that the possibility of gain, presented supraliminally or subliminally, can influence not only a brief physical exertion but also working memory (Bijleveld et al., 2010; Bustin et al., 2012; Capa et al., 2011a) over several seconds, suggesting that unconscious motivation has long-lasting effects. This finding is in agreement with the hypothesis that conscious and unconscious motivations regulate goal pursuit in a similar way and induces behaviors of engagement and perseverance to attain the goal (Custers and Aarts, 2010; Hassin et al., 2005; Dijksterhuis and Aarts, 2010; Wegner, 2002). Conscious and unconscious motivations may also mediate goal pursuit and behavior differently (for a review see Bijleveld et al., *in press*). Conscious awareness of a reward enables individuals to change the strategies they employ to attain that reward and to reflect on its meanings. For example, reward cues can boost effort regardless of awareness of rewards, but affect speed–accuracy tradeoffs only when individuals are conscious of the reward (Bijleveld et al., 2010). This interpretation fits well with the different stages of unconscious and conscious processes and their neuronal implementations (e.g., Dehaene et al., 2006; Van den Bussche et al., 2010).

Although these studies have important implications in extending unconscious motivational effects to our brain and behavior, unconscious motivation has not yet been shown to affect high-order executive control functions. Only a few studies using subliminal stimuli (i.e., those not related to motivation, such as an arrow to prime a response) have reported short-lived effects of subliminal stimuli on high-order executive control functions such as inhibitory (Boy et al., 2010; Van Gaal et al., 2008) and switching (Lau and Passingham, 2007) control processes. Little is known, however, about the potential long-lasting effects of unconscious motivation on executive control. Here building on research on unconscious motivation (Custers and Aarts, 2010;

Dijksterhuis and Aarts, 2010; Hassin et al., 2005; Wegner, 2002), we hypothesized that subliminal performance-contingent reward incentives have a lasting effect on task-switching, a key executive control process.

In task-switching paradigms, participants are required to switch between two or more tasks, with the currently relevant task signaled by a task–cue (the so-called cued task-switching paradigm). Generally, reaction times (RTs) are slower on task-switch than on task-repeat trials, an effect usually referred to as switch cost. Switch cost has been attributed to time consumed by executive control processes necessary for a change of task (Meiran et al., 2000; Monsell and Mizon, 2006; Rogers and Monsell, 1995). This may involve a number of sub-components, such as retrieving the rules and procedures required for task completion into working memory, initializing stimulus–response mappings, and suppressing activation of the previously active task-set (Meiran et al., 2000; Rogers and Monsell, 1995).

1.2. Conscious motivational influences on executive control

Consciousness is generally believed to be required for executive control (Dehaene et al., 2006). Although successful executive control is thought to depend on the activation strength of the cued task goal, the most important factor modulating this goal activation strength remains unclear. Motivational variables represent a likely candidate for this function, because motivational states are thought to regulate behavioral goal salience, the priority of goal pursuit, and criteria governing goal completion (Kruglanski et al., 2002). Nevertheless, researchers have only recently begun to focus on the neural mechanisms associated with the interactions between motivation and executive control (Pessoa, 2008, 2009).

Neurophysiological studies of behavior in primates have provided explicit evidence for motivational influences on neural mechanisms of executive control, by demonstrating that reward incentives can modulate delay-related activity in lateral prefrontal cortex neurons during maintenance periods of working memory tasks (Leon and Shadlen, 1999; Watanabe, 1996). Neuroimaging studies in humans have confirmed these findings by demonstrating reward-related modulations of activity in the prefrontal and parietal cortices and in associated neural systems during the performance of tasks involving working memory and executive control (Gilbert and Fiez, 2004; Kounieher et al., 2009; Krawczyk et al., 2007; Locke and Braver, 2008; Small et al., 2005; Taylor et al., 2004). Moreover, a recent study reported that motivation (i.e., a conscious possibility of earning money) could influence task-switching processes (Savine and Braver, 2010). In that study, the mixing cost, defined as the difference in performance between single-task blocks and blocks in which the tasks were intermingled, was reduced when money was at stake. Regions associated with pure effects of incentives, including subcortical regions such as the ventral and dorsal striata and the amygdala and cortical structures such as the posterior insula and ventral orbito-frontal cortex, were not sensitive to the mixing cost. Nevertheless, 4 of the 10 regions within the neural executive control network, including the dorsolateral prefrontal cortex, were

sensitive to both the mixing cost and incentive information. Savine and Braver (2010), however, found that reward had no influence on switch cost, defined as the difference in performance between switch trials and repeat trials within the same block. In contrast to the mixing cost, the switch cost, has been attributed to the need to reconfigure a task-set, rather than to a need to maintain two rather than one task-sets in an available state, or to differences between blocks in arousal, effort, or response criteria (Rogers and Monsell, 1995; Wylie et al., 2008). Moreover, distinct neurophysiological mechanisms mediate mixing costs and switch-costs (Wylie et al., 2008). In brief, it remains unclear whether conscious and unconscious reward cues can influence the switch cost and the different stages of switch processes (i.e., task preparation and execution).

1.3. Event-related potentials (ERPs) and neuroimaging studies during conscious task-switching

Previous work in human and animal cognitive neuroscience has implicated the lateral prefrontal and parietal cortices as centrally involved during task-switching (Crone et al., 2006; Dreher et al., 2002; Dreher and Berman, 2002; Johnston et al., 2007; Stoet and Snyder, 2007; Yeung et al., 2006). Assays of ERPs have identified two stages of switch processes that contribute to the switching cost (Brass et al., 2005; Gajewski et al., 2010a, 2010b; Lavric et al., 2008; Nicholson et al., 2006; Periañez and Barceló, 2009; Rushworth et al., 2002; Wylie et al., 2003). The first stage is induced by a cue before the arrival of the new stimulus. The ERPs elicited by presentation of a cue (cue-locked ERPs) differ for repeat and switch cues (Barceló et al., 2006; Brass et al., 2005; Jost et al., 2008; Miniussi et al., 2005; Nicholson et al., 2005, 2006; Periañez and Barceló, 2009). During the cue period, a parietal positivity emerges about 300–600 msec after presentation of the cue (Rushworth et al., 2002). The larger P3 after a cue–stimulus for a switch than for a repeat trial may reflect updating of task-sets in working memory (Jost et al., 2008; Nicholson et al., 2006; Periañez and Barceló, 2009). In addition, the appearance of a lasting negative slow wave—the contingent negative variation (CNV)—with a fronto-central distribution may be related to the preparation of all processes necessary for the task. This late negative component has been shown to be increased in trials in which participants invested preparatory effort (Falkenstein et al., 2003) and to be higher in mixed than in single-task blocks in the task-switching paradigm (Gajewski et al., 2010a). These results suggest that the decision to switch or repeat can be anticipated at cue-onset.

The second stage of switch processes is initiated only when a new stimulus is actually presented. The ERPs induced by the presentation of the target (target-locked ERPs) are also sensitive to transition type, *repeat* versus *switch* (Jost et al., 2008; Swainson et al., 2003). During task execution, fronto-central N2 was increased more in switch than in repetition trials (Gajewski et al., 2010a), suggesting that the amplitude of post-target N2 may be the main source of residual switch-costs, defined as the switch cost persisting even when there is ample time to prepare for the upcoming task (Rogers and Monsell, 1995). In contrast to findings during the cue period, the P3 while implementing a task-switch was found to be consistently smaller in switch than in repetition trials

(Nicholson et al., 2006; Rushworth et al., 2002), a decrease associated with implementation of the new task-set. These findings reveal that target processing also contributes to local switch cost.

1.4. Hypotheses

In the current study, we examined how motivation enhances preparatory executive control by separating the effects of performance-contingent reward incentives on cue-related versus target-related processing during task-switching. Participants were instructed that, if they responded correctly to each trial during a run of 13 trials, they would receive the reward presented at the beginning of the trial (Fig. 1).

Our hypotheses were based on the findings that both conscious and unconscious motivations regulate goal pursuit in similar ways and induce behaviors of engagement and perseverance to attain the goal (Custers and Aarts, 2010; Hassin et al., 2005; Dijksterhuis and Aarts, 2010; Wegner, 2002).

Our first hypothesis concerned the long-lasting effects of unconscious motivation on the percent of runs achieved, defined as 13 successive correct responses to obtain the coin at stake. The possibility of earning a large reward, whether conscious or unconscious, would increase performance and consequently be associated with an increase in EEG activity related to effort investment (i.e., a decrease of alpha and an increase of theta activity). Alpha activity has been reported to be inversely related to glucose metabolism in the brain, and effort investment has been associated with a suppression of alpha activity (Gevins et al., 1997). In contrast, theta activity has been found to increase in strength as tasks require more focused attention (Gevins et al., 1997).

Our second hypothesis concerned the brief effect of (un)conscious reward on task-switch processes and focused on RTs and ERPs. We hypothesized that participants would respond faster on repeat than on switch trials, particularly if they had the opportunity to earn more money (50 cents), whether knowledge was conscious or not. For the cue period, larger parietal P3 and fronto-central CNV were expected during switching than during repetition trials, mainly if participants had the opportunity to earn 50 cents, whether known subliminally or supraliminally. When a new stimulus was actually presented (task period), we expected a larger fronto-central N2 and a smaller parietal P3 during switching than during repetition trials, particularly if participants could earn 50 cents.

2. Methods

2.1. Participants

We evaluated 28 right-handed, naive volunteers (20 males, 8 females; age range 19–24 years) with corrected-to-normal vision. The study was approved by our local ethics committee. All participants provided written consent before participation and received the money they earned in the experiment. We utilized a 2 (reward presentation duration: 300 msec vs 27 msec) \times 2 (reward value: 1 cent vs 50 cents) \times 2 (trial type: switch vs repeat) within-participant trial design.

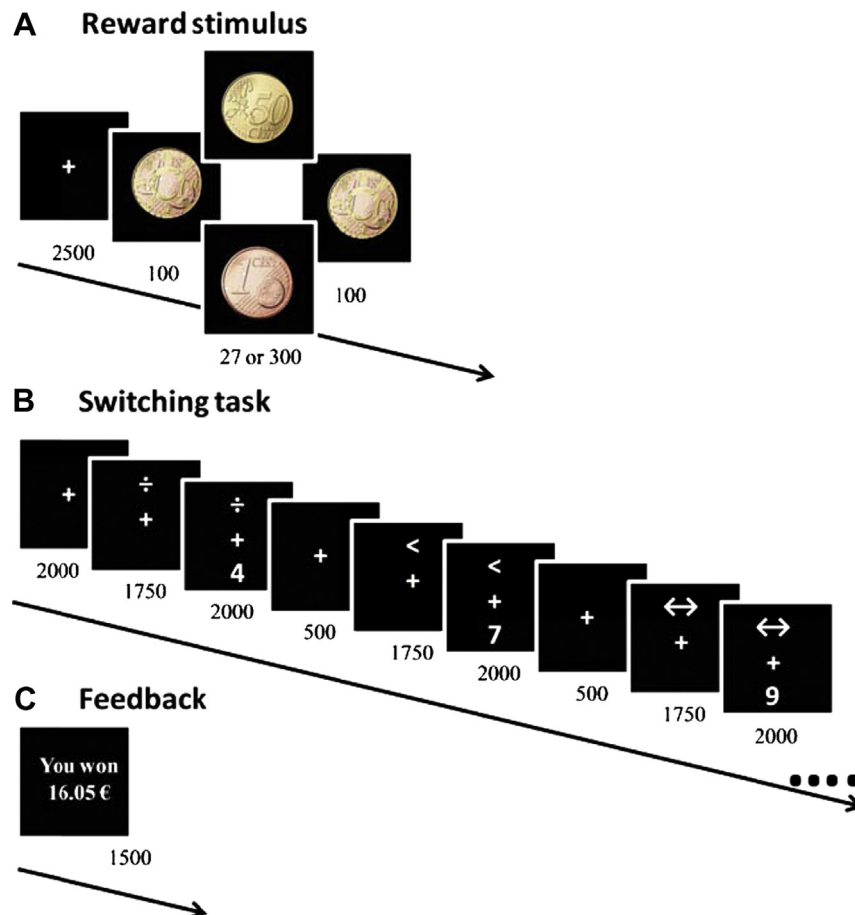


Fig. 1 – Design of the study. Successive screens are displayed during one run, with durations in milliseconds. Participants were instructed that, if they responded correctly to each trial of a run of 13 trials, they would (B) receive the reward displayed at the beginning of the run (A). Participants were informed of cumulative earnings at the end of each run (C). During each run participants had to perform three tasks (i.e., judging whether a number was odd or even, whether a number was smaller or greater than 5, and whether a number was inside or outside the continuum of 1–9) in an unpredictable sequence with a switch on 50% of trials.

2.2. Switch task and procedure

At the beginning of each run, a fixation cross appeared, followed immediately by a pre-mask, the reward stimulus, a post-mask (Fig. 1A), and the switch task (Fig. 1B). Participants were instructed that, if they responded correctly and before 2000 msec to each trial during a run of 13 trials, they would receive the reward presented at the beginning of the trial. Cumulative earnings were displayed at the end of each trial (Fig. 1C). Participants were informed that the reward stimuli were either 1 cent or 50 cents and would sometimes be difficult to perceive.

Fig. 1B summarizes the switching task. The task was composed of 64 runs of 13 trials (i.e., 16 runs each for the possibility to win 50 cents or 1 cent displayed either subliminally or supraliminally). A change of task was required on 50% of the trials. During each run, participants had to switch among three tasks: judging whether the number was odd or even (parity task), whether the number was smaller or greater than 5 (magnitude task), and whether the number was inside

(i.e., 3, 4, and 6, 7) or outside (i.e., 1, 2 and 8, 9) the continuum of 1–9 (inner/outer task). The task to be executed during each trial was signaled by a task–cue presented 1750 msec (cue–stimulus interval) before stimulus onset and 500 msec after the response to the previous trial (response–cue interval). As the three tasks occurred in an unpredictable sequence, anticipatory task-set reconfiguration processes could not be initiated until cue-onset (Meiran et al., 2000). The cues for the magnitude task were $<$ and $>$, the cues for the parity task were \div and \times , and the cues for the inner/outer task were \leftrightarrow and \nleftrightarrow . Cues during successive trials always differed, even on task-repeat trials. This procedure, using two cues per task, may allow measurements of the true switch cost, while controlling for the cost associated with cue change (Monsell and Mizon, 2006). Both the cue and the stimulus remained on the screen until the participant responded or until 2000 msec had elapsed. Stimuli were congruent (i.e., the stimulus was mapped to the same response in the three tasks) during 25% of the trials and incongruent (i.e., the stimulus was associated with a different response on at least one of the two unrelated

tasks) during 75% of the trials. Participants responded with either their left or right index finger. Stimulus–response mapping was counterbalanced across participants.

Each subject participated in an initial training session, performing single-task blocks of 60 trials each for parity, magnitude, and inner/outer tasks. This was followed by eight runs of eight trials each, in which the three tasks were intermingled, and finally the task itself. All stimuli were presented on a 75-Hz CRT screen.

2.3. Perceptual discrimination task

After the switch task, each participant performed a forced-choice test. Each trial consisted of masks and reward stimuli (Fig. 1A), followed by several choices presented simultaneously instead of the switch task. Participants pressed the 1 key if they saw “50 cents”, 2 if they saw “1 cent”, 3 if they guessed “50 cents”, and 4 if they guessed “1 cent”, with the participants told that accuracy, not speed, was important. These responses remained on the screen until a response was made.

2.4. Electrophysiological recording

Electroencephalographs were recorded from 32 AgCl active electrodes (Biosemi) mounted in an elastic cap. One electrode was placed at the Cz site according to the 10/20 system, with ear lobes (A1, A2) as references (averaged offline), and sampled at a rate of 2048 Hz (analog band pass .01–500 Hz, with off-line digital smoothing, 10 Hz cutoff). To monitor ocular artifacts, vertical and horizontal electrooculographic potentials (EOG) were bipolarly recorded.

2.5. Data analysis

Runs associated with an incorrect response were excluded from behavioral, power spectra and ERP analyses. Power spectra and ERPs were analyzed over the midline electrodes (FPz, AFz, Fz, FCz, Cz, CPz, Pz, and POz) (Adrover-Roig and Barceló, 2010; Gajewski et al., 2010a, 2010b; Nicholson et al., 2006). For RTs, error rates, and ERPs, the first trial of each run and all congruent trials were discarded. As the effect of switching can be modulated by overlapping stimulus–response assignments (Gajewski et al., 2010a; Rogers and Monsell, 1995), we focused on the incongruent trials. Congruent trials were excluded because all three tasks in these trials were associated with the same response, making it impossible to ascertain whether the relevant task was performed, and thus whether these trials were true switch or task-repeat trials. As investment of effort may be associated with a suppression of alpha activity and/or an increase of theta activity (Gevins et al., 1997), we conducted EEG analyses in the time from the first to the last trial of each run. Due to technical problems, EEG results were obtained from only 25 of 28 participants.

2.5.1. Power spectra analysis

Theta (3.5–7.5 Hz) and alpha (7.5–12.5 Hz) activities were calculated using the Fast Fourier Transform with a 2 sec Hanning window. Epochs with excessive muscle activity, eye movements or other artifacts (EEG exceeding $\pm 100 \mu\text{V}$) were

excluded from spectrum calculation. The values obtained for each 2 sec epoch and each electrode were averaged and log-transformed to standardize their distribution. After rejection of invalid epochs, data from a mean 190.52 (SD = 116.76) epochs per condition were analyzed.

2.5.2. ERP analysis

For both cue and task analyses, the epochs began 100 msec before cue or stimulus presentation (baseline correction) and ended 1750 msec (cue period) or 1000 msec (task period) afterward. Epochs with excessive muscle activity, eye movements or other artifacts (EEG exceeding $\pm 100 \mu\text{V}$) were excluded from analysis. During cue analyses, the mean number of epochs after the exclusion of invalid epochs was <10 for nine participants, perhaps because the long duration of cue epochs (1750 msec) had increased the occurrence of noise and artifacts. Data from these 9 participants were therefore discarded from cue ERP analyses. During task analyses, the mean of epochs after the exclusion of invalid trials was ≥ 10 for all participants. Finally, data from a mean 45.24 (SD = 16.43) trials per condition for the cue period and a mean 66.45 (SD = 12.26) trials per condition for the task period were analyzed.

The presence of the N2, P3, and CNV components was verified by inspecting the grand-average composite waveforms. Mean ERP amplitudes were determined relative to the N2 (210–230 msec), P3 (500–700 msec), and CNV (1100–1750 msec after cue-onset) components. N2 was regarded as the most negative peak in the 150–250 msec time range after target onset, and a latency bin of ± 10 msec was used to surround the N2 peak. P3 was found to be the most positive peak 450–750 msec after target onset, with a larger latency bin (± 100 msec) surrounding the P3 peak as it is a slower component. A fixed window was used to assess the development of the CNV (1100 msec) until the end of task preparation and the onset of task execution at 1750 msec.

3. Results

3.1. Behavior

When the percentage of correct runs was examined using two-way ANOVA (2 durations of reward presentation \times 2 reward values), we found that reward value had a main effect, with better performance for the high than the low reward [$F(1,27) = 20.1$, $p < .0001$, $\eta_p^2 = .41$] reflecting a general successful manipulation of reward. No other effect was found ($p > .18$ each). To ascertain that reward value had an effect during both durations of reward presentation, we performed planned complementary post-hoc comparisons. Participants performed better for the higher than for the lower reward, in both subliminal [$F(1,27) = 11.09$, $p < .002$, $\eta_p^2 = .29$] and supraliminal [$F(1,27) = 6.30$, $p < .02$, $\eta_p^2 = .19$] conditions (Fig. 2). We also assessed the effect of trial type by analyzing RTs and error rates by three-way ANOVA (2 durations of reward presentation \times 2 reward values \times 2 trial types). We found that switch had a main effect on RTs [$F(1,27) = 36.27$, $p < .001$, $\eta_p^2 = .57$]. As expected, participants responded faster during task-repeat than during task-switch trials. Reward value also had a main effect [$F(1,27) = 10.64$, $p < .003$, $\eta_p^2 = .28$], which interacted with duration of

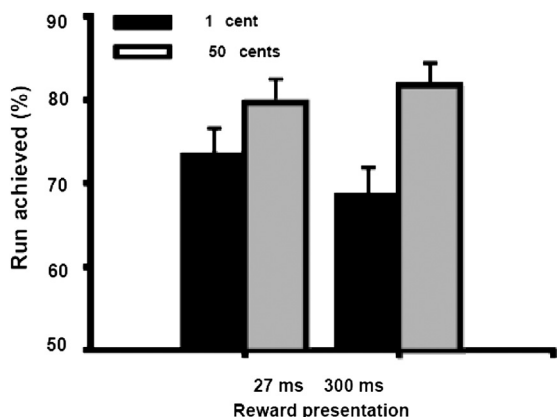


Fig. 2 – Percentage of correct runs achieved. Each run was composed of 13 trials and participants had to respond correctly to each trial to achieve the reward at the end of the run. Error bars represent standard errors of the mean.

presentation [$F(2,27) = 17.43$, $p < .001$, $\eta_p^2 = .39$]. Participants had better RTs when they had the possibility of earning 50 cents, but only in the supraliminal condition (Fig. 3A and B). Switch had a main effect on error rates, with higher error rates during task-switch than during task-repeat trials [$F(1,27) = 26.61$, $p < .0001$, $\eta_p^2 = .50$] (Fig. 3C and D). Moreover, participants had a tendency to make fewer errors in high- than in low-

reward conditions [$F(1,27) = 3.81$, $p = .06$, $\eta_p^2 = .12$] (Fig. 3C and D). No other effect was found ($p > .14$ each) for the percent of correct runs, RTs, and error rates.

3.2. Spectral results

To assess theta and alpha activity, we performed two preliminary 2 (duration of reward presentation) \times 2 (reward value) \times 8 (electrode sites) within-participant ANOVA to determine the most positive activity reached at a particular electrode position (i.e., site of interest). We found that electrode position had a significant effect [$F(7,168) = 24.09$, $p < .0001$, $\eta_p^2 = .50$; $F(7,168) = 34.46$, $p < .0001$, $\eta_p^2 = .59$], with the most important activity at FCz. As no other interaction between electrode and other factors was observed, follow up ANOVAs were performed for FCz only.

Two-way ANOVA of within-participant factors (2 durations of reward presentation \times 2 reward values), showed that reward value had a main effect [$F(1,24) = 8.02$, $p < .009$, $\eta_p^2 = .26$], with a greater decrease in alpha spectral activity, reflecting a more successful manipulation of reward when the higher reward ($M = 5.91$, $SD = 6.53$) than when the lower ($M = 5.26$, $SD = 5.19$) reward was at stake. Using planned complementary post-hoc comparison, we found that reward value had an effect during both durations of reward presentation. As expected, there was a decrease of alpha activity in subliminal [$F(1,24) = 4.43$, $p < .05$, $\eta_p^2 = .16$] and supraliminal [$F(1,24) = 6.82$, $p < .02$, $\eta_p^2 = .22$] conditions. No other effect was found ($p > .38$ each) for alpha

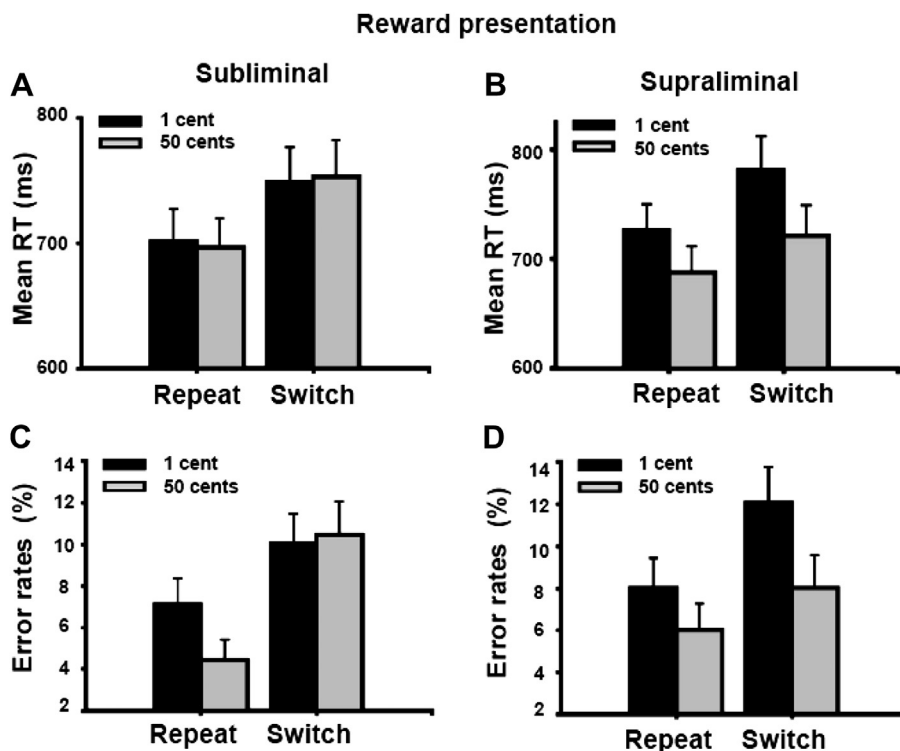


Fig. 3 – Mean reaction and error rates for correct runs as a function of trial type (repeat vs switch) when 1 cent and 50 cents were at stake under subliminal (A and C, respectively) and supraliminal (B and D, respectively) conditions. Error bars represent standard errors of the mean.

spectral activity. Evaluation of theta spectral activity by two-way ANOVA (2 durations of reward presentation \times 2 reward values) revealed no significant effects ($p > .27$ each).

3.3. Cue ERP results

Three preliminary 2 (duration of reward presentation) \times 2 (reward values) \times 2 (trial type) \times 8 (electrode sites) within-participant ANOVAs showed that electrode position had significant effects for the N2 [$F(7,105) = 10.83$, $p < .0001$, $\eta_p^2 = .42$], P3 [$F(7,105) = 5.26$, $p < .0001$; $\eta_p^2 = .26$] and CNV [$F(7,105) = 2.36$, $p < .03$, $\eta_p^2 = .14$] components, indicating that the most negative activity was at FCz (N2 and CNV) and the most positive activity at Pz (P3). As no interaction between electrode and other factors was found, follow up ANOVAs were performed for FCz and Pz only.

Each ERP component was examined by three-way ANOVA (2 durations of reward presentation \times 2 reward values \times 2 trial types) as within-participants factors. For the N2 component, no significant effect was found ($p > .12$ each). Switch had a significant effect, with a larger P3 at Pz in switch than in repeat trials [$F(1,15) = 5.53$, $p < .03$, $\eta_p^2 = .27$; Figs. 4 and 5A]. Reward value also had a main effect, with a more negative CNV at FCz for 50 cents than for 1 cent [$F(1,15) = 14.24$, $p < .002$, $\eta_p^2 = .49$]. Post-hoc planned comparisons showed that the effect of reward was present in both subliminal [$F(1,15) = 4.63$, $p < .05$,

$\eta_p^2 = .24$] and supraliminal [$F(1,24) = 5.49$, $p < .03$, $\eta_p^2 = .27$] conditions (Figs. 4 and 5B). No other effect was observed for the P3 and CNV components ($p > .12$ each).

3.4. Task ERP results

Two preliminary 2 (durations of reward presentation) \times 2 (reward values) \times 2 (trial types) \times 8 (electrode sites) within-participant ANOVAs showed that electrode position had significant effects on the N2 [$F(7,168) = 16.39$, $p < .0001$, $\eta_p^2 = .41$] and P3 [$F(7,168) = 4.16$, $p < .0001$, $\eta_p^2 = .15$] ERP components, with the most negative and positive activities at FCz and Pz, respectively. Since no interactions between electrodes and other factors were observed, three-way ANOVAs (2 durations of reward presentation \times 2 reward values \times 2 trial types) were performed only for FCz and Pz.

The N2 amplitude at FCz was larger in the switch than in the repeat condition [$F(1,24) = 10.20$, $p < .004$, $\eta_p^2 = .30$; Figs. 6 and 7A], whereas the P3 amplitude at Pz was smaller in switch than in non-switch trials [$F(1,24) = 20.28$, $p < .0001$, $\eta_p^2 = .46$; Figs. 6 and 7B]. The P3 amplitude at Pz was larger for 50 cents than for 1 cent, but only in the supraliminal condition, as suggested by the significant interaction between duration of reward presentation and value [$F(1,24) = 4.46$, $p < .04$, $\eta_p^2 = .16$; Figs. 6 and 7C]. No other effect was found for the N2 and P3 components ($p > .17$ each).

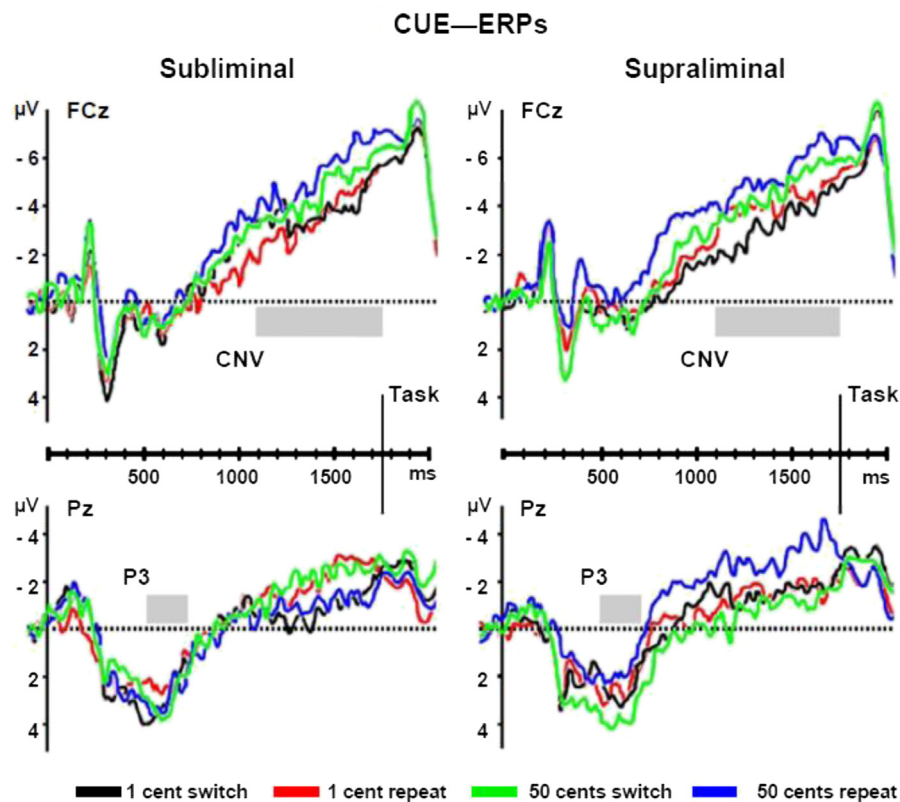


Fig. 4 – Epoch cue grand mean ERP waveforms as a function of experimental conditions. The gray bars indicate that CNV was significantly more negative at FCz when 50 cents than when 1 cent was at stake and that P3b was larger at Pz during switch than during repeat trials. The epoch task started 1750 msec after onset of cue presentation.

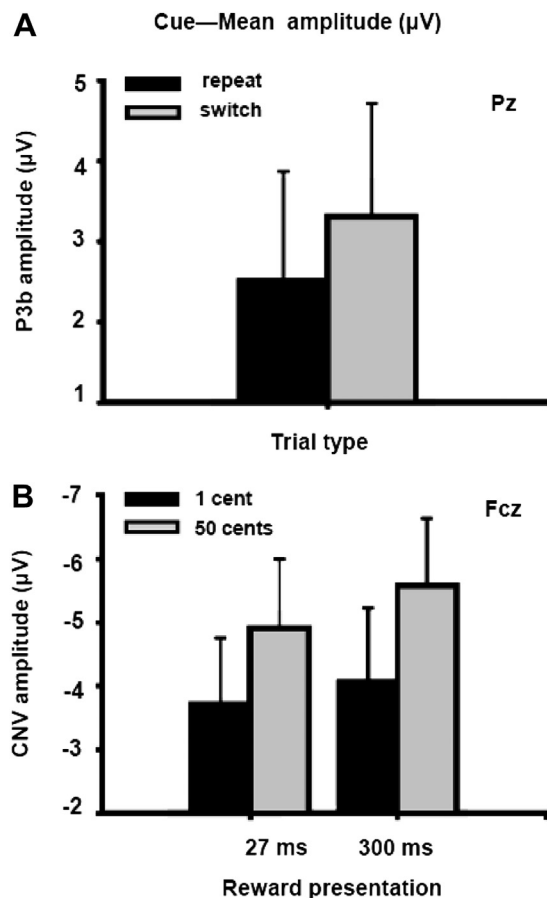


Fig. 5 – (A) Mean amplitude at the cue of the P3b at Pz as a function of trial type (repeat vs switch), and (B) mean amplitude of the CNV at FCz as a function of reward presentation duration and amount of reward. Error bars represent standard errors of the mean.

3.5. Prime visibility test

Debriefing participants before the prime visibility test revealed that none was able to report whether 1 cent or 50 cent coins were presented subliminally. We therefore analyzed prime visibility test results using the means of correct responses, defined as the participant having seen or guessed the correct coin. In the subliminal condition, the mean percentage of correct responses was 51.12 (SD = 5.12), which did not differ significantly from chance [$t(27) = 1.15$, $p = .26$]. In addition, the d' scores for each participant ($M = .06$; $SD = .26$) did not differ significantly from zero [$t(27) = 1.15$, $p = .26$].

3.6. Complementary analysis

We also tested the potential for subliminal effects to decrease over time on task. Two separate three-way ANOVAs (2 durations of reward presentation \times 2 reward values \times 2 times on task) were performed for RTs and alpha band activity. The first trial of each run was omitted, with the remaining run period divided into two phases: the beginning (trials 2–7) and the end

(trial 8–12). As the three tasks occurred in an unpredictable sequence within each run, these two phases (beginning and end) allowed the systematic inclusion of switch and repeat trials into each phase. Moreover, if subliminal processes collapsed after a few seconds, then a decrease would be observed after trial 7. We found no significant effects or interactions of RT and alpha band activity with time on task ($p > .29$ each).

4. Discussion

Conscious and unconscious motivations may regulate goal pursuit in similar ways and may induce engagement and perseverance behaviors to attain that goal (Custers and Aarts, 2010; Hassin et al., 2005; Dijksterhuis and Aarts, 2010; Wegner, 2002). However, it was unclear whether unconscious motivation could affect high-order executive control functions. A few studies using subliminal stimuli, but not related to motivation, found that subliminal stimuli had short-term effects on high-order executive control functions (Boy et al., 2010; Van Gaal et al., 2008; Lau and Passingham, 2007). Based on research on unconscious motivation (Custers and Aarts, 2010; Dijksterhuis and Aarts, 2010; Hassin et al., 2005; Wegner, 2002), we hypothesized that subliminal performance-contingent reward incentives would have a lasting effect on task-switching processes, a key executive control function.

4.1. Lasting effect of unconscious motivation

In both subliminal and supraliminal conditions, participants exhibited better performance, as shown by percentage of correct runs, for a higher than for a lower reward. This better performance may be due to a greater mobilization of resources, as shown by a stronger suppression of fronto-central alpha activity. Reduced alpha activity over different cortical areas, from frontal to parietal sites, has been reported during the performance of mental tasks, with the site depending on the task constraint (Gevins et al., 1997; Michels et al., 2008). These findings suggest that subliminal reward stimuli have an effect lasting over several seconds (mean time of run = 40.74 sec), or that the effect of such stimuli collapsed across time, with the behavioral and EEG effects observed present at the beginning of each run. No evidence for the latter hypothesis was found. Although zero-effects do not allow firm conclusions, we observed no differences in performance and alpha activity between the beginning and end of each run, suggesting that the effect of unconscious reward had not collapsed over time.

In contrast to our finding, many other studies have found that unconscious representations are short-lived (Dehaene et al., 2006; Greenwald et al., 1996). This difference may have been due to our use of stimuli intrinsically related to the goals and motivations of most people. Earning money may be one of the most important goals of daily life. Conscious and unconscious goal pursuits have been found to induce engagement and perseverance behaviors to attain these goals (Capa et al., 2011b; Custers and Aarts, 2010; Hassin et al., 2005; Dijksterhuis and Aarts, 2010). A description of the ERPs related to switch and RTs is now necessary to determine how this tonic or long-

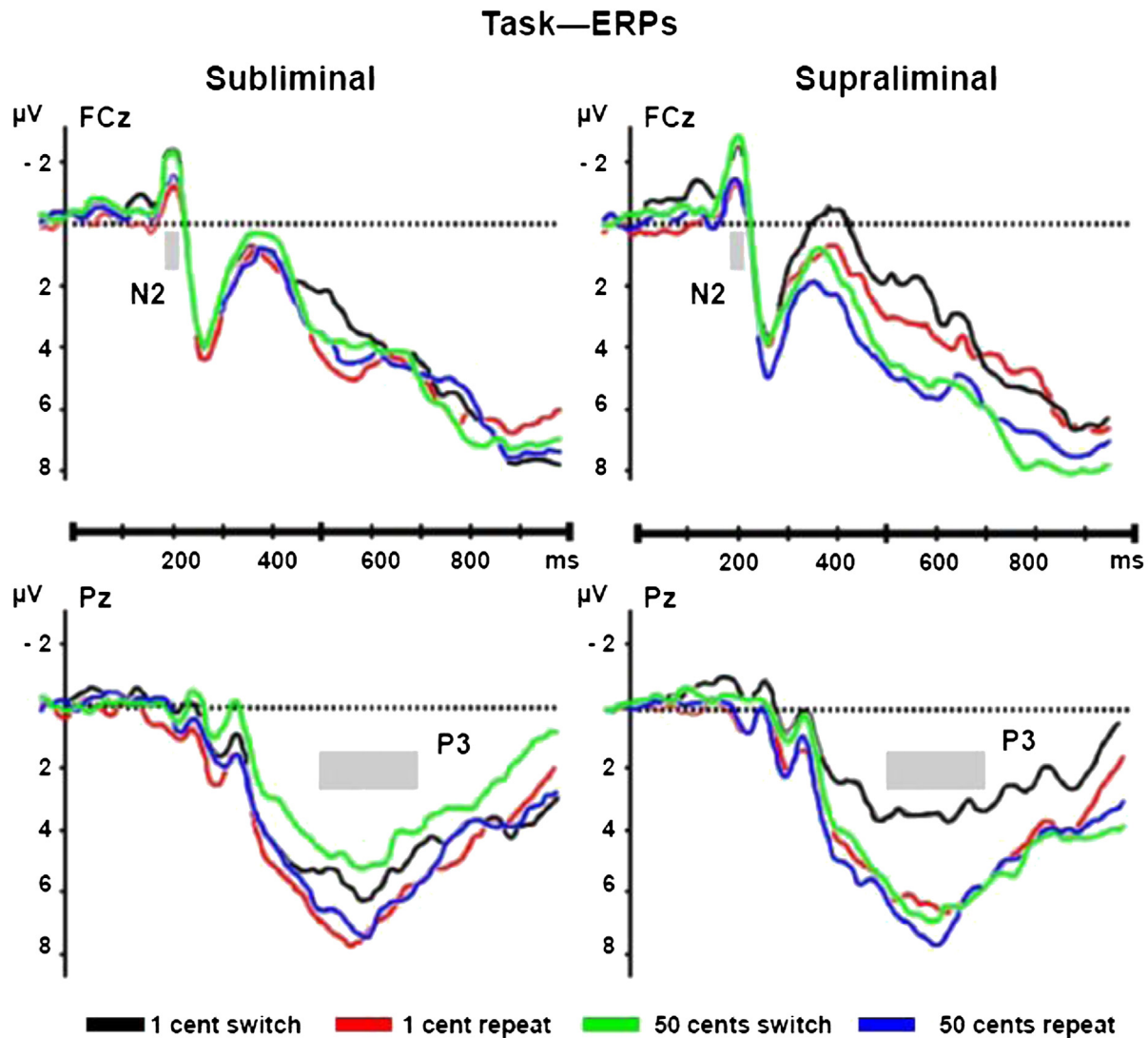


Fig. 6 – Epoch task grand mean ERP waveforms as a function of experimental conditions. Gray bars indicate that N2 was significantly larger at FCz and that P3b was significantly smaller at Pz in switch than in repeat trials, and that there was a significant interaction between duration of reward presentation and reward value on the amplitude of P3b at Pz.

lasting attentional effect translates into phasic or short-lived processes.

4.2. Effects of unconscious motivation on ERPs and RTs

We found that the switch cost obtained with our paradigm was robust, with longer RTs in switch than in repetition trials. Moreover, switch trials were associated with three distinct ERPs. The first concerned task preparation. Cues indicating a change in task were associated with a large amplitude parietal positivity, which was maximal at around 500–700 msec. Several neurophysiological studies investigating ERP components in task-switching have reported a larger parietal positivity in the preparation interval for switch than for repetition trials (Jost et al., 2008; Nicholson et al., 2006; Periañez and Barceló, 2009). Consistent with these findings, the differential switch-related positivity we observed may reflect the

preparatory updating of S–R mapping. Larger late P3 amplitudes have been observed with longer than with shorter cue–stimulus intervals (Periañez and Barceló, 2009), and a negative correlation was observed between late P3 amplitudes and behavioral switch-costs (Barceló et al., 2006). The two other ERPs were related to task execution. Following stimulus onset, task-switch trials showed a fronto-central differential negativity compared with task-repeat trials, in agreement with findings on task-switching (Gajewski et al., 2010a; Kieffaber and Hetrick, 2005; Nicholson et al., 2006; Rushworth et al., 2002; Wylie et al., 2003), usually related to conflict and response selection (Folstein and Van Petten, 2008; van Veen and Carter, 2002). Finally, parietal P3 implementing a task-switch task was consistently smaller in switch than in repeat trials, in agreement with earlier results (Rushworth et al., 2002; Nicholson et al., 2006), a finding traditionally interpreted as associated with better updating, organization and

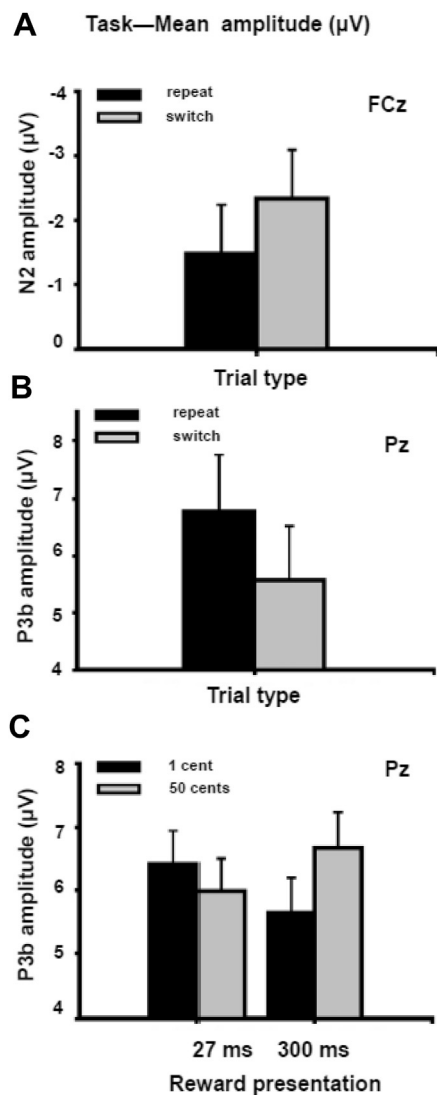


Fig. 7 – During task performance, mean amplitudes of the N2 at FCz (A) and of the P3b at Pz (B) as a function of trial type (repeat vs switch) and of the P3b at Pz (C) as a function of duration of reward presentation and reward value. Error bars represent standard errors of the mean.

implementation in the new task-set. Taken together, these findings indicate that manipulation of task-switching is generally successful and support previous findings that the anticipatory reconfiguration of a task-set on switch trials is associated with a cognitive process distinct from that involved in task execution (Astle et al., 2006; Brass et al., 2005; Jost et al., 2008; Kieffaber and Hetrick, 2005; Meiran et al., 2000; Rogers and Monsell, 1995; Wylie et al., 2003, 2008).

In assessing the effects of unconscious motivation on ERPs and RTs, we found that, during task preparation, the CNV of the fronto-central area was higher when a high reward was displayed, whether subliminally or supraliminally. Similar conscious and unconscious motivations have been observed during the preparation stage. RTs were better when the reward was 50 cents but only when participants were aware of

the reward amount. In the subliminal condition, no RT difference was observed, suggesting participants were more cautious. Congruently, modulation of the parietal P3 was larger when 50 cents was at stake, but only under supraliminal conditions. In brief, a larger P3 amplitude at parietal during task execution was associated with a greater investment in working memory and better performance (i.e., faster RTs). This was confirmed by the negative correlation we observed between P3 and mean RT during task execution ($r = -.26$, $p < .001$). This interpretation is in good agreement with the “context updating” hypothesis for the P3b (Donchin and Coles, 1988), which proposes that P3b amplitude is proportional to the amount of working memory revision required during task performance. However, in the subliminal condition, this association between P3 amplitude and RTs was not observed, suggesting that the execution stage of switching may be influenced only by conscious rewards and that unconscious stimuli cannot penetrate this stage. Alternatively, participants may have invested too much working memory for a conscious reward of 50 cents, because the task required a correct, not a rapid, response. This result is consistent with findings showing that a conscious reflection on reward can lead people to concentrate too much on a task (e.g., Baumeister et al., 2011; Capa et al., 2011a). Additional studies with different time constraints on response (brief and long periods) are required to differentiate between these two possibilities. If participants are cautious in performing a task for an unconscious reward, then decreasing the response time limit would induce greater efforts in task execution. If, however, an unconscious reward cannot influence the execution stage of switching, because consciousness is required for this stage, then there would be no significant difference between short and long responses. In brief, even if, at the tonic level (i.e., several seconds) the brain does not care whether the goal to earn money is primed subliminally or supraliminally, there would be a difference at the phasic level or short-lived processes.

Similar to previous studies (Bijleveld et al., 2010; Van den Bussche et al., 2010), our empirical study confirmed the different stages of unconscious and conscious processes (Dehaene et al., 2006; Van den Bussche et al., 2010). When participants are consciously aware of a reward, they can change their strategies to attain that reward. In contrast to unconscious reward, conscious reward processing may involve higher-level cognitive functions located in the prefrontal cortex that are related to decision making (Dehaene et al., 2006). Although conscious thought about a problem may be helpful in reaching more rational decisions, conscious thought can also interfere with sound decision making (Dijksterhuis and Aarts, 2010). People can often weigh the relative importance of attributes quite well unconsciously, whereas conscious thought may lead to biases in the weighting process. For instance, conscious thought tends to attach too much weight to verbal but not enough weight to non-verbal information.

Similar to previous findings (Savine and Braver, 2010), we found that both unconscious and conscious rewards had no effect on switch cost. The reasons that reward incentives did not modulate switching cost remain unclear, although they may be associated with the task used to investigate task-switching. Rule switching, when participants determine the rules for a correct response based on feedback, was shown to

be characterized by greater engagement of the dorsolateral prefrontal cortex (Ravizza and Carter, 2008), whereas perceptual switching, as shown here and by Savine and Braver (2010), was associated with greater recruitment of the parietal cortex. The prefrontal cortex is critical in achieving goals (Miller and Cohen, 2001), suggesting that unconscious and conscious rewards may only affect task-switching involving the prefrontal cortex (e.g., Ravizza and Carter, 2008). Finally, switch-costs also reflect interference effects due to persistent activation of a previous task-set and to stimulus based priming of an irrelevant task-set (Waszak et al., 2003). These interference effects persist even after a long preparation for the upcoming task, suggesting that these effects cannot be overcome by top-down control processes (Vandierendonck et al., 2010). In addition, interference has been found to vary for certain characteristics of the tasks, and interference was shown to occur in task repetition trials (Waszak et al., 2003). Thus, if interference effects were crucial in task-switching performance in our study, these effects may have prevented modulation of switch-costs.

In conclusion, we have shown here that, at the tonic level (i.e., several seconds), unconscious and conscious rewards can have long-lasting effects during cued task-switching performance, with a higher percentage of runs achieved. At the phasic level or with short-lived processes, we found that reward had no effect on switch cost, whereas ERPs indicated that unconscious and conscious motivations are similar during early stages of task-switching preparation but differ during task performance.

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