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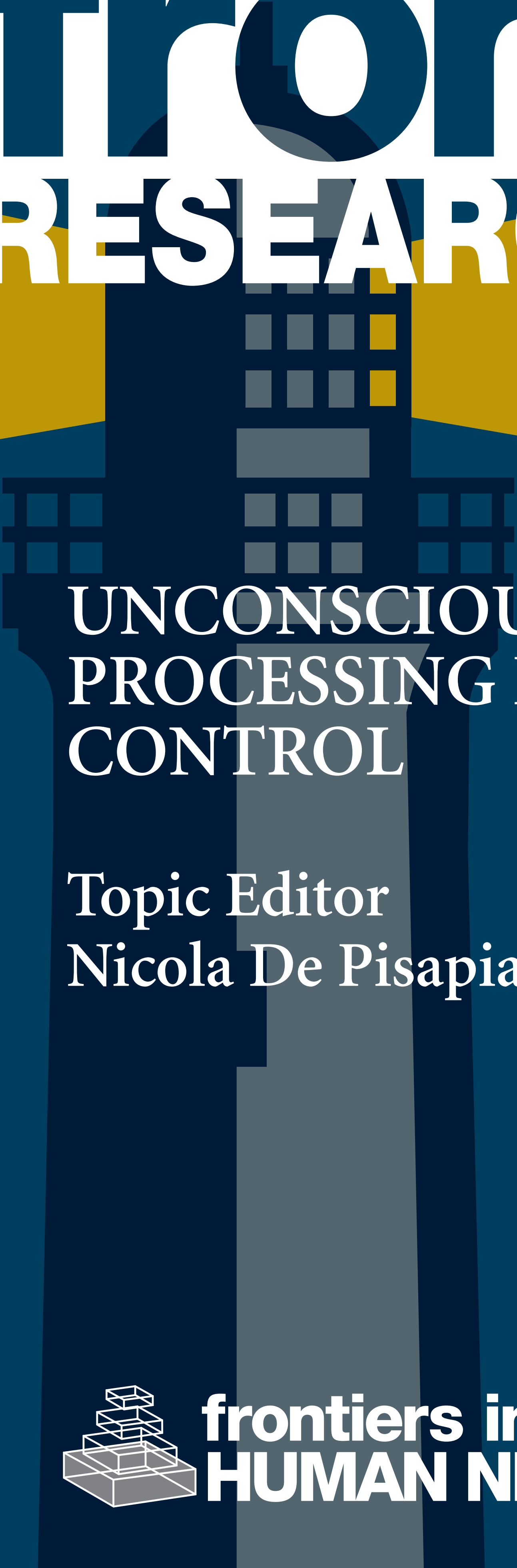

UNCONSCIOUS INFORMATION PROCESSING IN EXECUTIVE CONTROL

Topic Editor
Nicola De Pisapia

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UNCONSCIOUS INFORMATION PROCESSING IN EXECUTIVE CONTROL

Topic Editor:
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Image by Nicola De Pisapia

The aim of this Frontiers special issue is to review and further explore the topic of unconscious processing in executive control. Executive control refers to the ability of the human brain – mostly associated with prefrontal cortex activity – to regulate the processing involved in the execution of novel or complex goal-directed tasks. Previous studies or models of human cognition have assumed that executive control necessarily requires conscious processing of information. This perspective is in line with common sense and personal introspection, which suggest that our choices are intentional and based on conscious stimuli. Nevertheless, in the last few years several behavioural and cognitive neuroscience studies have put under scrutiny this assumption. Cumulating evidence is now showing that prefrontal executive control can involve or be triggered by unconscious processing of information, with consequent effects on observed behaviours.

One of the main methods adopted to study such unconscious mechanisms is masked priming, consisting in presenting visually masked stimuli, which nonetheless are shown to affect goal-directed behaviour or influence constructs linked to executive control and prefrontal cortex activity (e.g., task-set representation, response inhibition, conflict monitoring, error detection, reward processing, emotion regulation and task switching).

This area of research is relatively young, and - while scientific evidence is emerging – no general consensus has been reached yet on how to interpret these early findings: some researchers accept that executive control can involve unconscious processing, others momentarily put aside - in first approximation - this issue, others criticize this possibility on theoretical grounds (e.g., pointing to the need of better definitions of terms such as control, conflict and consciousness) or based on experimental findings.

At this stage, it appears necessary that researchers in the field make a collective effort to deepen the understanding of the unconscious mechanisms involved in executive control. This special issue will focus on neuroscience, but it will welcome contributions on purely behavioural and psychophysiological studies, patient reports, computational investigations, as well as philosophical and historical analyses of the relationship between executive control and consciousness. In particular, we encourage experts in this field to submit contributions in the form of:

a) reviews, opinions and discussions on existing literature concerning unconscious processing of information in executive control;
b) original research articles (both behavioural-only and neuroimaging studies) on unconscious processing of information in executive control;
c) discussions and opinions on new methodologies to investigate this issue (e.g., other than masked priming, which has been the technique of choice in most of the existing studies).

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EDITORIAL
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Unconscious information processing in executive control

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This Frontiers Research Topic includes original experimental studies and reviews on unconscious processing in executive control. Executive control refers to the ability of the human brain—mostly associated with prefrontal cortex activity—to regulate the execution of novel or complex goal-directed tasks. Previous studies and models of human cognition have assumed that executive control necessarily requires conscious processing of information. This perspective is in line with common sense and personal introspection, which suggest that our choices and action regulations are intentional and based on conscious stimuli.

Nevertheless, in the last few years several behavioral and cognitive neuroscience studies have put under scrutiny this assumption. Cumulating evidence is now showing that executive control can involve or be triggered by unconscious processing of information, with consequent effects on observed behaviors. One of the main methods adopted to study such unconscious mechanisms is masked priming, consisting in presenting visually masked stimuli, which nonetheless are shown to affect goal-directed behavior or influence constructs linked to executive control and prefrontal cortex activity (e.g., task-set representation, response inhibition, conflict monitoring, error detection, reward processing, emotion regulation, and task switching). Other methods have been adopted, such as auditory masking or implicit regularities in stimulus presentations.

This area of research is relatively young, complex, and challenging, but very exciting. While scientific evidence is emerging—no general consensus has been reached yet on how to interpret these early findings. Some researchers accept that executive control can involve unconscious processing, others momentarily put aside—in first approximation—this issue, and others criticize this possibility on theoretical grounds (e.g., pointing to the need of better definitions of terms such as control, conflict, and consciousness) or based on experimental findings.

This Frontiers Research Topic is born from the idea that it is time that researchers in cognition make a collective effort to deepen the understanding of the unconscious mechanisms involved in executive control. The book includes articles from top researchers in the field, and it is organized in a first section with a selection of original research articles, and a second section with review and hypothesis papers.

SECTION I: ORIGINAL RESEARCH ARTICLES

In the first article of the experimental section, Fuchs and Ansorge (2012) address the question of whether inhibition has the same characteristics in conscious and unconscious executive control. In particular, they focus on the so-called Inhibition of Return (i.e., slower responses to attended than unattended positions), which in previous studies was considered to indicate an automatic capture of visual attention driven by unconscious cues. In a series of experiments, the authors find that Inhibition of Return can only be obtained with conscious cues, thus suggesting that consciousness might be a necessary condition for inhibition.

In the next research article, Gaillard et al. (2012) investigate the relationship between inner speech and consciousness in executive control, and they find that articulatory suppression specifically impairs exclusion performance by interfering with inner speech.

In the next article, Schlaghecken et al. (2012) use a masked prime task to test the hypothesis that typical aging is associated with a selective deficit in inhibitory function, affecting both low-level motor, and higher-level executive control.

Finally for this section, Zedelius et al. (2012) argue in favor of a unique role of consciousness in efficient allocation of effort during cognitive control processes, and they investigate the delivery of unconscious rewards during task executions. They find that people fail to integrate unconsciously perceived reward value with conscious expectancies concerning the attainability of rewards, which leads them to poor and unsubstantiated choices.

SECTION II: REVIEW AND HYPOTHESIS ARTICLES

Moving on to the next section, McBride et al. (2012) discuss findings concerning object affordances, alien limb syndrome, the visual grasp reflex, subliminal priming, and subliminal triggering of attentional orienting. Their suggestion is that automatic motor activation might form an intrinsic part of all behavior, rather than being categorically different from conscious actions.

Desender and Van den Bussche (2012) critically review the topic of adaptation to response conflict, which is a key component of executive control processes, and they discuss how it can be induced by unconscious information processing.

Kiefer (2012) provides an overview of the latest research on executive control influences on unconscious information processing. He discusses his attentional sensitization model of unconscious information processing, in which unconscious processing is only elicited if the cognitive system is configured accordingly, namely it depends on attentional amplification of task-congruent processing pathways as a function of task-sets.

Meiran et al. (2012) review and discuss the seemingly paradoxical loss of control associated with states of high readiness to execute a plan, termed "intention-based reflexivity." They suggest that the neurocognitive systems involved in the preparation of novel plans are different than those involved in preparation of practiced plans, and discuss the idea that proactive control (acting in advance of the experienced response conflict) tends to be a relatively rigid construct.

Horga and Maia (2012) suggest that conscious and unconscious processes might be implemented by the same neural substrates and largely perform the same neural computations. What characterizes these processes is time, namely more durable neuronal firing for conscious processes, and less durable neuronal firing for unconscious processes, but both of them can cause behavior.

In the final article, Prabhakaran and Gray (2012) expand the idea of unconscious information processing in executive control by exploring and reviewing the societal unconscious influences, such as priming of goals, social hierarchies, and interpersonal interactions.

This collection of papers offers an exciting overview of the field of unconscious processing in executive control, and hopefully it will help other researchers of cognition to further explore this young and exciting field.

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ORIGINAL RESEARCH ARTICLE
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Inhibition of return is no hallmark of exogenous capture by unconscious cues

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Inhibition of irrelevant information and response tendencies is a central characteristic of conscious control and executive functions. However, recent theories in vision considered Inhibition of Return (IOR: slower responses to attended than unattended positions) to be a hallmark of automatic exogenous capture of visual attention by unconscious cues. In the present study, we show that an unconscious cue that exogenously captures attention does not lead to IOR. First of all, subliminal cues with a contrast different from a searched-for target contrast capture attention independently of their match of contrast polarity to the search criteria. This is found with a short cue-target interval (Exp. 1). However, the same cues do not lead to IOR with a long cue-target interval. The lack of IOR is also verified for several intermediate intervals (Exp. 2), for high-contrast cues and low-contrast targets (Exp. 3), and with lower luminance cues presented on a CRT screen (Exp. 4). Finally, no capture effect but IOR is found for consciously perceived anti-predictive cues (Exp. 5). Together the results support the notion of a double dissociation between IOR and exogenous capture and are in line with a decisive role of consciousness for inhibition.

Keywords: vision, attention, subliminal, cueing, inhibition of return, attentional capture, exogenous capture

INTRODUCTION

Conscious control allows inhibition of irrelevant information (cf. Baars, 2002; Botvinick et al., 2004), but inhibition has also been found with task-relevant unconscious stimuli (Lau and Passingham, 1998). Recently, however, Mulckhuyse and Theeuwes (2010) argued that Inhibition of Return (IOR) could be a hallmark of exogenous capture of visual attention by unconscious cues. In this context, *exogenous capture* denotes attentional capture by a truly task-irrelevant stimulus, and *IOR* denotes that participants respond slower to recently attended but now ignored positions than to less attended positions (cf. Taylor and Klein, 1998). For example, presenting a cue with a cue-target Stimulus Onset Asynchrony (SOA) of less than about 300 ms at one of two possible target positions, attentional capture to the cue is reflected in facilitated responses to a target at the same position (SP) as the cue. This facilitation is found relative to the responses to a target at a different position (DP) than the cue. However, with SOAs of more than about 300 ms, this cueing effect reverses into IOR and responses will often be slower in SP than DP conditions.

Mulckhuyse and Theeuwes (2010) argued that exogenous capture and IOR by unconscious cues are flip sides of one shared process of initially activating and subsequently inhibiting one cued location representation within the retinotopic map of the Superior Colliculi, a midbrain structure that is fed by the visual input of the magno-cellular projection from the retinal ganglion cells. Support for this supposition comes from the observations that the Superior Colliculi indeed seem to play an active role (I) in exogenous capture (cf. Rafal et al., 1991) and (II) in unconscious capture (cf. Ansorge, 2003; Fuchs and Ansorge, 2012) as well as (III) in IOR (cf. Dorris et al., 2002).

However, it is also possible that exogenous capture and IOR are brought about by dissociable cortical structures rather than by one shared sub-cortical structure (e.g., Lupiánez, 2010; Hu and Samuel, 2011). For example, exogenous capture (e.g., Itti et al., 1998) and unconscious capture (e.g., Zhaoping, 2008) could also rely on processing of visual input in early visual cortex (e.g., V1) whereas IOR could be brought about by a different cortical area, for example, posterior parietal cortex (e.g., Mayer et al., 2004; Toffanin et al., 2011). According to this line of reasoning, it might well be that exogenous unconscious capture and IOR are less tightly coupled to one another than assumed so that at least in some instances exogenous unconscious capture could be observed without subsequent IOR. This is of some relevance. If it can be shown that unconscious exogenous capture and IOR are not flip sides of one another, one could not rely on one of the effects, for example, IOR, to infer with certainty that the other effect, for example, exogenous capture, has also taken place. This, however, is exactly the conclusion that has been drawn by Mulckhuyse and Theeuwes (2010).

In addition, research with clearly visible cues has shown that IOR is not only a consequence of exogenous attentional capture. To reiterate, exogenous capture can only be demonstrated when the cue is truly irrelevant and does not fit to the top-down control settings of the participants. However, IOR can also be found after top-down contingent capture. For example, having their participants search for either abrupt onset targets or color targets, Gibson and Amelio (2000) demonstrated that abrupt onset cues only captured attention and led to subsequent IOR if the participants searched for abrupt onset targets. Capture and IOR, however, were absent when an abrupt onset cue was used but targets were defined by colors. Gibson and Amelio (2000) concluded that both, capture and IOR depended on a match of the abrupt onset cues to the top-down control settings of their participants which were set up to search for the targets (cf. Folk et al., 1992; see also Pratt et al., 2001; Prinzmetal et al., 2011).

This was the point of departure for the present study. We wanted to test whether IOR is indeed a necessary consequence of exogenous unconscious capture. Exogenous capture would only be demonstrated where two conditions are fulfilled: visual cues would have to (I) not match the participants' top-down search templates for relevant features and (II) be uninformative about target positions (cf. Folk et al., 1992). Because criterion (I) must not be met to find IOR (e.g., Gibson and Amelio, 2000) and because Mulckhuyse et al. (2007) only used cues of a task-relevant contrast polarity, it is possible that unconscious IOR reflected top-down contingent capture based on a fit of the cue's contrast polarity to the search settings rather than (a consequence of) exogenous capture by a truly irrelevant cue. Therefore, it still needs to be tested whether IOR is or is not a hallmark of unconscious exogenous attentional capture.

In five Experiments, our participants reported the presence of targets in unconsciously cued SP and DP conditions. Attentional capture was verified as faster target detection in SP than DP conditions with short SOAs (cf. McCormick, 1997). IOR was tested as slower target detection in SP than DP conditions with long cue-target SOAs. Crucially, we also varied whether or not the cues matched the top-down search sets for contrast polarity. Our cues either had the same contrast polarity as the searched-for targets, or the cues had the opposite contrast polarity to the searched-for targets. Thus, only the same- but not the opposite-polarity cues matched the participants' top-down search templates for target contrasts. For example, if participants searched for dark targets, dark cues were top-down matching but light cues were non-matching. If it is true that IOR is a hallmark of unconscious exogenous capture, we expected IOR in the non-matching conditions with an opposite-polarity cue because it has been shown that truly exogenous capture does not depend on a match of the contrast polarity sign (Steinman et al., 1997). In the final Experiment 5 we also tested attentional effects of anti-predictive consciously and unconsciously perceived cues (cf. McCormick, 1997). If consciousness has a supportive role for inhibition, we expected to find IOR with conscious cues even if it was lacking with unconscious cues.

EXPERIMENTAL SECTION

EXPERIMENT 1

Methods

In Experiment 1 (with a TFT monitor) eight participants searched for black (23 cd/m^2) and another eight for white (122 cd/m^2) targets against a gray background (72.5 cd/m^2, Weber contrast for both targets was $c_w = \pm 0.68$). **Figure 1A** depicts sample trials: the cue (a ring of 3.0° × 3.0° size and of a strength of 0.25°) was presented left or right on the screen (with an eccentricity of 6.7°) 16 ms before two placeholder rings (of the same size) appeared: one in the middle and the other one on the opposite side of the screen. The target was a disk (of 1.9° × 1.9° size) and could appear either centered in the left or right ring. In the short SOA condition, the target appeared along with the placeholders. In the long SOA condition, the target was shown 1 s after the onset of the two placeholder rings. The target was shown in 80% of the trials. The cue and the targets were equally likely left or right, and the target was equally often at the cued position (SP condition) or opposite of the cue (DP condition). The cue was, therefore, uninformative with respect to the target position and the cue was also invisible (or hard to see) because of strong flicker fusion with the placeholder onsets during the tiny interval between the cue and the two other placeholder rings. For every participant a same- or an opposite-polarity cue (with luminance values as for the respective targets) equally likely preceded the target. Different conditions were presented in a randomized sequence of 200 trials. To assess capture (in the short SOA) and IOR (in the long SOA), participants reported the target's presence by a button press. After the target-detection task, participants were informed that one of the rings (i.e., the cue) appeared one frame earlier than the others, and instructed to report the cue position. Participants pressed the left button if they saw the cue on the left and the right button if they saw the cue on the right. In this task, the participants' unconsciousness about the cues would

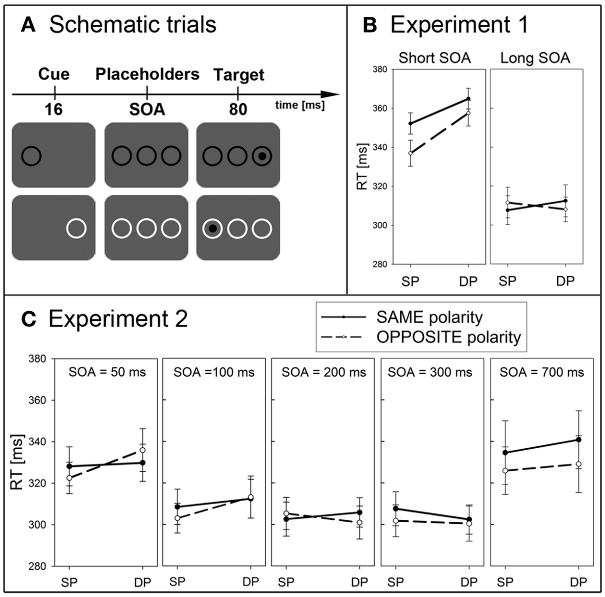

FIGURE 1 | (A) Depicted are schematic trials. The top row shows a dark target on the right side, cued by a dark cue at the left side (same-polarity and DP condition). The bottom row also depicts a dark target, but preceded by a light cue and again on the different position (opposite-polarity and DP condition). **(B)** Depicted are mean RTs (between 280 and 380 ms) and standard errors of the mean (error bars) of all participants, plotted separately for the short (left panel) and long SOA (right panel) of Experiment 1. Results are shown for SP (left side of each panel) and DP conditions (right side of each panel), and plotted separately for same- (solid lines) and opposite-polarity cues (dashed lines). **(C)** Depicted are mean RTs (between 280 and 380 ms) and standard errors of the mean (error bars) of all participants, plotted separately for the five different SOAs (separate panels, from left to right for SOA = 50, 100, 200, 300, and 700 ms) of Experiment 2.

be reflected by a small d' value, with $d' = 0$ indicating chance performance.

Results

Participants performed very well on the target-detection task (mean d' of target detection $= 4.3$). Only target-present trials were included in the analyses, and trials with incorrect responses (i.e., misses; 1.1%) and outliers [reaction times (RTs) deviating more than two standard deviations from the mean; 4.0%] were excluded. See also **Figure 1B** for the RT results. A repeated-measurements ANOVA of the mean correct RTs with the variables *cue position* (SP vs. DP), *cue contrast polarity* (same vs. opposite), and *SOA* (short vs. long) led to the following results. Responses to targets preceded by an SP cue (327 ms) were generally faster than in DP conditions (336 ms), as indicated by a main effect of cue position, $F(1,15) = 13.6$, $p < 0.01$, $\eta_p^2 = 0.48$. Participants also responded faster in the long SOA (RT = 310 ms) than the short SOA (RT = 353 ms), as indicated by a significant main effect of SOA: $F(1,15) = 101.8$, $p < 0.001$, $\eta_p^2 = 0.87$, and in opposite- (RT = 328 ms) than same-polarity (RT = 334 ms) conditions, reflected in a main effect of contrast polarity, $F(1,15) = 8.5$, $p < 0.05$, $\eta_p^2 = 0.36$. Significant two-way interactions between cue polarity and SOA, $F(1,15) = 5.2$, $p < 0.05$, $\eta_p^2 = 0.26$, and between cue position and SOA $F(1,15) = 22.7$, $p < 0.001$, $\eta_p^2 = 0.60$, prompted *post-hoc* Bonferroni-adjusted t-tests of cueing effects (SP vs. DP) split up for each combination of SOA and contrast polarity. Importantly, these tests revealed a significant cueing effect in the short SOA for both, same-polarity (SP: RT = 352 ms, DP: RT = 365 ms, $p < 0.01$) and opposite-polarity conditions (SP: RT = 337 ms, DP: RT = 358 ms, $p < 0.01$). In the long SOA, no significant effect was found, neither for same-polarity (SP: RT = 308 ms, DP: RT = 312 ms, $p = 0.19$) nor opposite-polarity conditions (SP: RT = 312 ms, DP: RT = 308 ms, $p = 0.50$).

After finishing the target-detection task, participants were asked whether they had been aware of the cue (i.e., one of the rings starting earlier) during the target-detection task. All participants reported a subjective unawareness of the cues during the target-detection task. However, as an objective measure of cue awareness, we next ran a cue-discrimination task, and d' for cue detection was calculated from this task. To be precise, in the cue-discrimination task, correct reports of cues on the right counted as hits, and incorrect reports of cues on the right as false alarms, and d' was calculated as the difference between the z-transformed probabilities of the hits minus the z-transformed probabilities of the false alarms. d' will be zero in the case of chance performance (or invisibility of the cues) and can infinitely increase with an ever increasing discrimination performance. On average, cue detection was above chance level [mean $d' = 0.24$, t-test against zero, $t(15) = 2.5$, $p = 0.024$]. However, restricting our analysis to only the worst cue discriminators among the participants, the participants remained completely unaware of the cue [mean $d' = -0.02$, $t(7) = -0.55$, $p = 0.60$], and yet the RT effects reported above could be replicated, with significant main effects for cue position and SOA, and a significant interaction between these variables reflecting that there was a cueing effect in the short SOA ($p < 0.01$) but no IOR in the long SOA ($p = 0.27$).

Discussion

We found cueing effects in the short SOA for both, same- and opposite-polarity conditions. This is evidence for exogenous capture because only in the same- but not in the opposite-polarity conditions, the cues would have matched the top-down search template for target contrasts. In addition, exogenous capture was also found with the participants that remained unaware of the cues. This demonstrated exogenous unconscious capture. Crucially, however, we could not find any evidence of IOR in the long SOAs. This finding is at variance with the claim that IOR is a hallmark of unconscious exogenous capture. Before we could conclude this with certainty, additional possible explanations for the lack of IOR had to be tested. First, the long SOA of 1 s could have been an unfortunate choice, if IOR occurred earlier and had vanished after 1 s. To test this possibility, we conducted Experiment 2, where we used five intermediate SOAs between 50 and 700 ms. Second, the luminance values of our stimuli and background were different to previous studies that reported IOR (cf. Mulckhuyse et al., 2007). This might be crucial because lower target contrasts can lead to larger IOR compared to higher contrasts (e.g., Hunt and Kingstone, 2003). This was tested in Experiment 3. Third, the current Experiment differed in two further respects from the study by Mulckhuyse et al. (2007): the use of a CRT screen and the cues' luminance values. These changes were addressed in Experiment 4.

EXPERIMENT 2

Methods

With 18 new participants, we used the same experimental set up as in Experiment 1, except for the SOAs that were 50, 100, 200, 300, or 700 ms, presented in a random order.

Results and discussion

Participants performed very well on the target-detection task (mean $d' = 4.2$). Again, only target-present trials were analyzed, and trials with incorrect responses (2.1%) and outlying RTs (further 2.3%) were excluded. For the RT results see **Figure 1C**. A repeated-measurements ANOVA of the mean correct RTs with the variables *cue position* (SP vs. DP), *cue contrast polarity* (same vs. opposite), and *SOA* (five steps) led to a significant main effect of SOA, $F(4,68) = 11.2$, $p < 0.001$, $\eta_p^2 = 0.40$ (for SOA of 50 ms: RT = 329 ms, SOA of 100 ms: RT = 309 ms, SOA of 200 ms: RT = 304 ms, SOA of 300 ms: RT = 303 ms, and SOA of 700 ms: RT = 333 ms). All other tests failed to reach significance.

All participants reported a subjective unawareness of the cues during the target-detection task, but the cue detection-block revealed above chance accuracy for the shortest and longest SOA (mean d's = 0.35 and 0.44 respectively, $p < 0.05$), whereas the cue remained below the objective threshold in the other SOAs (all ps > 0.05).

Discussion

In Experiment 2 we used the exact same procedure as in Experiment 1 except for the SOAs. Although the cues initially captured attention (at a very short SOA of Exp. 1), the capture effect seems to wear off very rapidly, as indicated by non-significant effects for all SOAs in Experiment 2. This result also rules out the possibility that IOR occurred at an earlier interval between 50 and 700 ms.

EXPERIMENT 3

In Experiment 3, we tested whether IOR depended on contrast strength. In past research it was found that lower target contrasts can lead to larger IOR compared to higher target contrasts (e.g., Hunt and Kingstone, 2003). For our tests, we used high-contrast cues preceding low-contrast targets at four different SOAs.

Methods

With 14 new participants, we used a similar experimental set up as in Experiment 1. Here, all participants searched for a low-contrast target (10.5 cd/m^2, Weber contrast $c_w = 0.62$) preceded by a high-contrast cue (104 cd/m^2, Weber contrast $c_w = 15.0$) against a black background (6.5 cd/m^2). The reported luminance values match those used in the study by Hunt and Kingstone (2003). Furthermore, we also varied the SOAs: In half of the trials, the target again appeared simultaneously with the two other placeholders, whereas in the other half of the trials the target followed equally often after an SOA of 800, 1,000, or 1,200 ms. The additional long SOAs of 800 and 1,200 ms were chosen corresponding to the study by Hunt and Kingstone (2003; where the interval between cue and target onset was 1,160 ms, and between cue offset and target onset 860 ms). The target again appeared equally often at the same (SP) or different position (DP) as the cue. Conditions were presented in a randomized sequence of 240 trials including 20% catch trials. Cue visibility was assessed in a second block consisting of 60 trials.

Results

Participants performed well in the target-detection task even though the target was difficult to see (mean $d' = 2.1$). Again, only target-present trials were analyzed, and trials with incorrect responses (20.7%) and outlying RTs (4.4%) were excluded. See **Figure 2A** for the RT results. First, we tested for IOR in only the long SOAs, and calculated a repeated-measurements ANOVA with the variables *cue position* (SP vs. DP), and *SOA* (800, 1,000, or 1,200 ms) on RTs. There was neither a significant main effect of SOA nor cue position, nor a significant interaction between these variables (all $ps > 0.18$). Therefore, we collapsed across different long SOAs for a subsequent ANOVA, with the variables *cue position* (SP vs. DP), and *SOA* (short vs. long) on RTs. Again we found a significant main effect for SOA, $F(1,13) = 63.1, p < 0.001, \eta_p^2 = 0.83$, indicating faster responses in the long SOAs (RT = 377 ms) than in the short SOA (RT = 510 ms). A significant interaction between cue position and SOA, $F(1,13) = 7.7,\ p < 0.05,\ \eta_p^2 = 0.37$, and *post-hoc* Bonferroni-adjusted *t*-tests revealed a significant cueing effect in the short SOA (SP: RT = 504 ms, DP: RT = 516 ms, $p < 0.05$) and no effect in the long SOAs (SP: RT = 377 ms, DP: RT = 376 ms, $p = 0.94$).

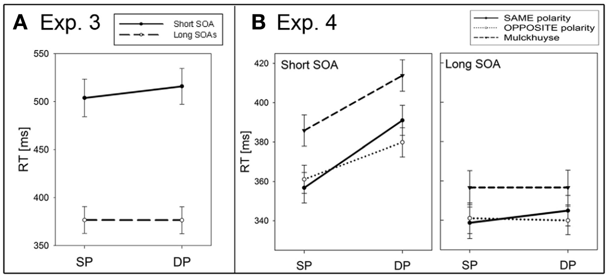

FIGURE 2 | (A) Depicted are the results (mean RTs between 350 and 550 ms) of Experiment 3. Mean RT was faster if the cue was at the same position (SP) as the target than if the cue was at a different position (DP) than the target. This was found with a short cue-target stimulus onset asynchrony (SOA; solid line) but not with a long SOA (dashed line). **(B)** Analogous results (mean RTs between 325 and 425 ms) of Experiment 4 are plotted separately for the short (solid line) and long SOAs (dashed line), for three different conditions separately (see figure legend). For further details refer to the Methods sections of Experiments 3 and 4.

Importantly, again, all participants reported a subjective unawareness of the cues during the target-detection task. Objectively, participants performed above chance level in the cue-detection task (mean $d' = 1.65, p < 0.001$), and performance did not differ across SOAs, $F(3,39) < 1$.

Discussion

When presenting a low-contrast target cued by a high-contrast cue, we failed to find IOR in the long SOAs, although we found a cueing effect in the short SOA. This finding rules out that the lack of IOR in the present Experiment 1 could be explained by the high contrast strength of the target relative to the background, which facilitated target perception and undermined the attentional effect of the cues.

The results of Experiment 3 also prompted a question: because target- and cue-detection were both objectively, and almost equally bad, does this mean that the participants were unaware of the low-contrast targets? Not necessarily. During the target-detection task, participants actively searched for the targets. Although active top-down search for a stimulus does not always lead to stimulus awareness (e.g., Ansorge et al., 2009), a wealth of research suggests that active search for a stimulus has the potential to increase stimulus awareness (cf. Mack and Rock, 1998; Simons, 2000). Therefore, our participants probably saw the targets but failed to subjectively see the cues during target-detection because they actively searched for only the targets. By the same token, the participants probably became increasingly aware of the cues during cue-detection, when they actively searched for the cues. In line with this, participants indeed occasionally reported becoming also subjectively aware of the cues during the cue-detection task. In conclusion, we can understand that during target-detection the participants were aware of the targets and at the same time unaware of the cues, if we take into account the awareness-mediating role of target-directed vs. cue-directed active search.

EXPERIMENT 4

Experiment 4 was conducted on a CRT screen and participants searched for three different target contrasts in three separate blocks: black targets, white targets, and targets matching the luminance conditions reported in Mulckhuyse et al. (2007).

Methods

Experiment 4 used the same procedures as Experiment 1, except for the following changes: A CRT monitor (as in Mulckhuyse et al., 2007) was used instead of a TFT screen. All participants ($N = 18$) searched for three different target luminances in three separate blocks (with different block orders balanced across participants): one block with black ($20\,\mathrm{cd/m^2}$) targets against a gray background ($55\,\mathrm{cd/m^2}$; Weber contrast $c_w = -0.8$), one with white ($90\,\mathrm{cd/m^2}$) targets against the same gray background ($c_w = +0.8$)—in these blocks, a cue of either the same or the opposite contrast polarity preceded the target,—and a third block with targets and backgrounds with the same luminance values as reported in Mulckhuyse et al. [i.e., a target in dark-gray ($13\,\mathrm{cd/m^2}$) against a black background ($5\,\mathrm{cd/m^2}$), $c_w = 1.6$]. The latter condition will henceforth be referred to as the "Mulckhuyse condition." In this condition, only cues matching the target luminance were used. In all blocks, the target was either presented along with the other placeholders (SOA = 0 ms) or with an SOA of 1 s. Again, participants searched for the targets in a random sequence of all conditions within each block of 200 trials.

Results

Participants performed very well on the target-detection task (mean $d' = 4.7$). Again, only target-present trials were analyzed, and trials with incorrect responses (1.1%) and outlying RTs (2.7%) were excluded. See **Figure 2B** for the RT results. A repeated measurements ANOVA of the mean correct RTs with the variables *cue position* (SP vs. DP), *cue condition* (same-polarity vs. opposite-polarity vs. Mulckhuyse condition), and *SOA* (short vs. long) led to a significant main effect for SOA, $F(1,17) = 54.0$, $p < 0.001$, $\eta_p^2 = 0.76$, with shorter RTs in the long (RT = 346 ms) than in the short SOA (RT = 381 ms). Furthermore, responses in SP conditions (RT = 357 ms) were generally faster than in DP conditions (RT = 371 ms), as indicated by a significant main effect of cue position, $F(1,17) = 185.1$, $p < 0.001$, $\eta_p^2 = 0.92$. Also, responses in the Mulckhuyse condition were generally slower (RT = 378 ms) compared to the same- (RT = 358 ms, $p < 0.001$) and opposite-polarity condition (RT = 355 ms, $p < 0.001$), indicated by a main effect for cue condition, $F(2,34) = 46.2$, $p < 0.001$, $\eta_p^2 = 0.73$. We found significant interactions between cue condition and cue position, $F(2,34) = 5.4$, $p < 0.05$, $\eta_p^2 = 0.24$, between cue condition and SOA, $F(2,34) = 7.1$, $p < 0.01$, $\eta_p^2 = 0.30$, and between cue position and SOA, $F(1,17) = 82.4$, $p < 0.001$, $\eta_p^2 = 0.83$. *Post-hoc* Bonferroni adjusted *t*-tests revealed significant cueing effects (i.e., faster responses to SP than DP cued targets) for all cue conditions in the short SOA (RT differences, i.e., RTs to DP cues – SP cues: for same-polarity = 34 ms, for opposite-polarity = 19 ms, and for the Mulckhuyse condition = 28 ms, all $ps < 0.001$). No significant results were found for the long SOA at all (RT differences, i.e., RTs to SP cues – DP cues: for same-polarity = –6 ms, for opposite-polarity = 1 ms, and for the Mulckhuyse condition = 0 ms, all $ps > 0.09$), indicating a lack of IOR in all conditions.

Importantly, again, all participants reported a subjective unawareness of the cues during the target-detection task. Also, although objective cue detection was worse in the Mulckhuyse condition (mean $d' = 1.32$) than in the same-polarity (mean $d' = 1.98$; $p < 0.05$) and the opposite-polarity condition (mean $d' = 2.21$; $p < 0.01$), participants performed above chance level in all conditions (all $ps > 0.001$).

Discussion

Experiment 4 showed that capture can be found even with cues that are subjectively not seen but that IOR is not observed under these conditions. These findings rule out that the CRT screen or the different luminance values of the cues and background used in the study by Mulckhuyse et al. (2007) as compared to the present Experiments 1–3 accounted for the absence of IOR in the current study. Experiment 4 is a failure to replicate IOR under the conditions of Mulckhuyse et al. (2007).

EXPERIMENT 5

In Experiment 5, we tested whether IOR occurs for anti-predictive supraliminal cues. This manipulation allows for a strategic use of the cues (cf. McCormick, 1997; Ansorge, Kiss et al., 2011). Since the target can be found at the position opposite to the cue (i.e., in the DP conditions) in the majority of the trials, we expected faster responses to DP than SP conditions, when the cues were visible, but not for invisible cues. In the Introduction, we argued for a critical role of consciousness during inhibition. Therefore, in two separate blocks the cues were either rendered visible or invisible, and they appeared at the position opposite to the target on the majority of trials. We expected a qualitative difference. Based on the supportive role of consciousness for inhibition IOR was expected in supraliminal cueing conditions. Based on the lack of IOR in the preceding experiments of the present study, however, no IOR was expected in the subliminal cueing conditions.

Methods

With 16 new participants, we used a similar experimental set up as in Experiment 1, except for the following changes. First, in two separate blocks, the cues were either invisible (as in the preceding experiments) or visible. Cue visibility was achieved in one block by omitting the two additional placeholder rings (see **Figure 3A**). Block sequence was balanced across participants. Second, targets were preceded by DP cues in 75% and by SP cues in only 25% of the target-present trials. In this manner, IOR was encouraged.

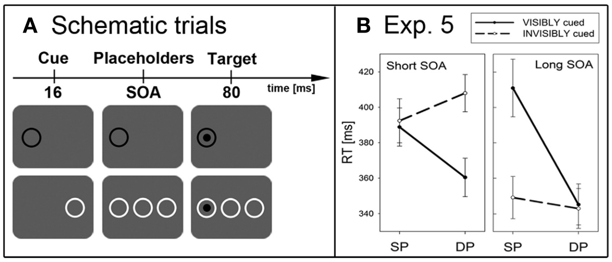

FIGURE 3 | (A) Depicted are schematic trials of Experiment 5. The top row shows a visibly cued dark target (same-polarity and SP condition). The bottom row depicts an invisibly cued light target (opposite-polarity and DP condition). **(B)** Results (mean RTs between 330 and 430 ms) of Experiment 5 are plotted separately for the short (left panel) and long SOA (right panel), and for visibly (solid line) and invisibly cued targets (dashed line).

Different conditions were presented in a randomized sequence of 240 trials including 20% catch trials. Cue awareness was assessed in a final block consisting of 80 trials.

Results

Participants performed very well on the target-discrimination task (mean $d' = 4.1$). Again, only target-present trials were analyzed, and trials with incorrect responses (1.9%) and outlying RTs (2.8%) were excluded. See **Figure 3B** for the RT results. A repeated-measurements ANOVA with the variables *cue position* (SP vs. DP), *cue contrast polarity* (same vs. different), *cue visibility* (visible vs. invisible), and *SOA* (short vs. long) on mean correct RTs led to the following results. Responses in SP conditions (RT = 385 ms) were generally slower than in DP conditions (RT = 364 ms), as indicated by a significant main effect of cue position, $F(1,15) = 41.7$, $p < 0.001$, $\eta^2_\text{p} = 0.74$. Furthermore, participants generally responded faster in the long SOA (RT = 362 ms) compared to the short SOA (RT = 387 ms), as indicated by a significant main effect for SOA, $F(1,15) = 15.5$, $p < 0.01$, $\eta^2_\text{p} = 0.51$. We found four significant two-way interactions: between cue position and contrast polarity, $F(1,15) = 5.9$, $p < 0.05$, $\eta^2_\text{p} = 0.28$, between cue position and awareness, $F(1,5) = 46.1$, $p < 0.001$, $\eta^2_\text{p} = 0.76$, between cue position and SOA, $F(1,15) = 22.2$, $p < 0.001$, $\eta^2_\text{p} = 0.60$, and between awareness and SOA, $F(1,15) = 49.9$, $p < 0.001$, $\eta^2_\text{p} = 0.77$. Importantly, *post-hoc* Bonferroni-adjusted *t*-tests revealed a cueing effect (SP: RT = 392 ms, DP: RT = 408 ms, $p < 0.05$) in the invisible condition for the short SOA, whereas participants responded slower to SP (RT = 389 ms) compared to DP cues (RT = 360 ms, $p < 0.01$) when the cue was visible. In the long SOA, we again found no significant effect for invisible cues (SP: RT = 349 ms, DP: RT = 343 ms, $p = 0.36$), and IOR for visible cues (SP: RT = 411 ms, DP: RT = 345 ms, $p < 0.001$).

Cue detection was worse for invisible cues (mean $d' = 1.92$) than for visible cues (mean $d' = 3.51$; $p < 0.01$), but participants performed above chance level in both conditions (both $ps > 0.001$).

Discussion

The results of Experiment 5 show a double dissociation between cueing effects and IOR: for anti-predictive visible cues IOR but no capture was found, whereas for unconscious or invisible cues a capture effect but no IOR was obtained (cf. McCormick, 1997). This emphasizes that IOR and exogenous capture are based on two separate mechanisms, mediated by conscious control or being more independent of control, respectively. With the visible cues, IOR was even found with the short SOA, which is in line with prior findings (cf. Tassinari and Berlucchi, 1993). One caveat of the present experiment is that the visual stimulation in the visible and invisible condition cannot be directly compared. For instance, the placeholders could have undermined capture and IOR only in the unconscious cueing conditions. Evidently, this was not the case regarding capture because capture was only found in the invisible conditions with the additional placeholders. However, future research should be devoted to understand the confounded roles of invisibility and placeholders on the lack of IOR, too.

A second important aspect of the results of Experiment 5 is that the subliminal cues used throughout this study were truly subliminal because if participants would have been aware of the cues, their strategic use for inhibition would have led to faster responses in DP than SP conditions in the subliminal condition, too.

GENERAL DISCUSSION

We found attentional capture by unconscious cues. This was reflected in faster target detection in SP than DP conditions in the short cue-target interval for both, same- and opposite-polarity conditions (Exp. 1), and these effects did not differ for very low-contrast targets (Exp. 3) or varying luminance values of cues or targets (Exp. 4). In contrast to some previous research (cf. Ansorge et al., 2010), we observed subliminal attentional capture that was independent of the match of the cue to the searched-for target features (here: target contrast polarities). Thus, exogenous capture by the cues was ensured at least in the opposite-polarity conditions. In the current study we found an independence of the cueing effect from the match between the contrast polarity of the unconscious cue and the participants' search set.

Crucially, however, and in line with our opinion that IOR is not a hallmark of unconscious exogenous capture, we did not find IOR with longer cue-target SOAs (see also McCormick, 1997; Scharlau et al., 2006). This was found even when different intermediate SOAs were used (Exp. 2). Therefore, the lack of IOR was very likely not due to an unfortunate choice of SOAs. In addition, because we found exogenous capture with the same cues under short SOA conditions (in Exp. 1), the lack of IOR cannot be ascribed to an absence of attentional capture. Finally, whether or not the cues were relevant did not change this major result. Crucially, IOR but no capture was found in a control condition with consciously perceived cues (Exp. 5). Together, these results support the conclusion that capture and IOR do not necessarily rely on the same mechanism (cf. Prinzmetal et al., 2011), and must not be brought about by one shared two-phase process in the Superior Colliculi (cf. Mulckhuyse and Theeuwes, 2010). Instead, the fact that capture could be observed without subsequent IOR would be equally well in line with different origins of capture and IOR, for instance, an origin of capture in the early visual cortex (cf. Zhaoping, 2008) and an origin of IOR in posterior parietal cortex (cf. Toffanin et al., 2011).

Unexpectedly and in contrast to Mulckhuyse et al. (2007), our participants were able to objectively discriminate between the cues as indicated by significant d' values. This was the case even in conditions that were very similar in all important respects to the protocol of Mulckhuyse et al. (2007; present Exp. 4). Maybe some characteristic such as the exact shape of the cues (which were rings in our study but disks in Mulckhuyse et al., 2007) has led to a lower visibility in Mulckhuyse et al. (2007) study but our results are well in accordance with the known sensitivity of the visual system for temporal asynchronies between unconsciously cued and uncued stimuli (cf. Scharlau and Ansorge, 2003).

Note also that the currently found average ability of the participants to objectively discriminate between the cues does not cast doubts on our conclusion that we measured an unconscious capture effect. This is so because first, in Experiment 1, we showed very similar capture effects in objectively unconscious and conscious cueing conditions, that is, for participants that performed on chance level when discriminating the cues, a capture effect in the short SOA and no IOR in the long SOA was found, too. In addition, due to flicker fusion all of our participants failed to see the cues and therefore claimed to at least subjectively have remained unaware of the cues. All participants, therefore, passed a subjective criterion of unconscious cueing during target detection and this alone allows the conclusion that cueing was brought about unconsciously (Merikle et al., 2001). Crucially, the participants' inability of a strategic use of the anti-predictive unconscious cues clearly showed that the subliminal cues used in the present study were not consciously perceived (Exp. 5).

CONCLUSION

IOR can be found with visible and top-down matching cues (cf. Gibson and Amelio, 2000) and IOR is unreliable with unconscious exogenous capture (see our experiments above). Together, these observations are in line with a double dissociation between IOR on the one hand and unconscious exogenous capture on the other. The results are also suggestive of a decisive role of task sets and consciousness for inhibition in general and, thus, in good agreement with major theories of inhibitory executive functions (cf. Kunde, 2003; Botvinick et al., 2004; Ansorge, Fuchs et al., 2011). For instance, using conscious and unconscious cueing, IOR was stronger with conscious cues and sometimes selectively found with conscious cues (cf. Ivanoff and Klein, 2003). It is our opinion that the unreliable IOR effects of unconscious cues that have sometimes been reported in the literature (Mulckhuyse et al., 2007) could well be due to side factors unrelated to (I) the invisibility of the cues and (II) the nature of capture (i.e., whether capture was exogenous or not), such as the exact way in which the cue visibility has been reduced (cf. Ivanoff and Klein, 2003) or even the exact sample of participants (cf. Mulckhuyse et al., 2007). The absence of IOR after unconscious exogenous cueing in the present study certainly refutes Mulckhuyse and Theeuwe's (2010) assumption that IOR would be a hallmark of unconscious exogenous capture.

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The influence of articulatory suppression on the control of implicit sequence knowledge

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The present study investigated the consciousness-control relationship by suppressing the possibility to exert executive control on incidentally acquired knowledge. Participants first learned a sequence of locations through a serial reaction time (SRT) task. Next, to assess the extent to which the incidentally acquired knowledge was available to executive control, they were asked both to generate the learned sequence under inclusion instructions, and then to avoid the generation of the learned sequence under exclusion instructions. We manipulated the possibility for participants to recruit control processes in the generation task in three different conditions. In addition to a control condition, participants generated sequences under inclusion and exclusion concurrently with either articulatory suppression or foot tapping. In a final recognition task, participants reacted to old vs. new short sequences (triplets), and judged, for each sequence, whether it had been presented before or not. Results suggest that articulatory suppression specifically impairs exclusion performance by interfering with inner speech. Because participants were nevertheless able to successfully recognize fragments of the training sequence in the recognition task, this is indicative of a dissociation between control and recognition memory. In other words, this study suggests that executive control and consciousness might not be associated in all circumstances.

Keywords: inner speech, articulatory suppression, sequence learning, control

Executive control and consciousness are typically assumed to be associated (see Moors and De Houwer, 2006; Hommel, 2007 for reviews): one can only control the knowledge that one is aware of. Dehaene and colleagues "neural workspace" hypothesis, for instance, explicitly rules out the possibility that an unconscious process can modulate high-level, conscious processes (Dehaene and Changeux, 2004). However, evidence that executive control is possible in the absence of awareness has recently been obtained with masked priming (Heinemann et al., 2009; van Gaal et al., 2009; Kiefer and Martens, 2010; Capa et al., 2011).

Using a different method, the present study aimed at assessing whether knowledge that one cannot control nevertheless remains available to awareness. Participants first learned a sequence of locations through a serial reaction time (SRT) task (Nissen and Bullemer, 1987). Next, to assess the extent to which the incidentally acquired knowledge was available to executive control, they were asked both to generate the learned sequence under inclusion instructions, and then to avoid the generation of the learned sequence under exclusion instructions. Comparing the knowledge produced when people are directly instructed to recall it and when they are directly instructed to avoid its recall makes it possible to assess the extent to which people are able to control the influence of the acquired knowledge (Destrebecqz and Cleeremans, 2001; Wilkinson and Shanks, 2004). Finally a direct recognition task assessed awareness of the material. Crucially, people's ability to control the expression of the learned knowledge was manipulated by asking participants to perform a secondary task during generation. Thus, in addition to a control condition, participants generated sequences under inclusion and exclusion instructions concurrently with either articulatory suppression or foot tapping. The rationale behind this manipulation stems from the well-established relationship between language, inner speech, and cognitive control. Cragg and Nation (2010) recently surveyed the studies showing a parallel development of language abilities and cognitive control. Indeed, after the seminal "Thought and language" book by Vygotsky (1962), there is no doubt that language plays a role in guiding children's own thinking and behavior. However, the exact implication of inner speech in cognitive control continues to be debated. Cragg and Nation (2010) suggest that language may be implicated in selecting and activating the relevant task set, in keeping track of the task (or item) order, and in retrieving the relevant task goal, especially when conflicting information is present. In the following, we briefly review evidence that suppressing inner speech is indeed detrimental to controlled processes.

SUPPRESSING INNER SPEECH AS A MEANS OF INTERFERING WITH EXECUTIVE CONTROL

One of the foremost methods to study the role of inner speech in higher-level cognition consists of "relatively simple articulatory interference procedures" (de Guerrero, 2005, p. 108). For example, in seeking to induce perseverative errors in healthy participants and compare their performance with frontal patients, Dunbar and Sussman (1995) administered the Wisconsin Card

Sorting Test (WCST) concurrently with either an articulatory suppression or a tone detection secondary task. They observed more perseverative errors when a category is changed for the first time, in the articulatory suppression condition only. In other words, perseverative errors can be induced in the WCST by blocking inner speech, because participants loose track of the task rules.

Concurrent articulatory suppression has also been extensively used to hinder task preparation in the task-switching paradigm. In such studies, participants complete or verify lists of addition and subtraction problems, or perform parity, magnitude, letter, color, or shape judgments in blocked vs. alternating form (Baddeley et al., 2001; Emerson and Miyake, 2003; Miyake et al., 2004; Saeki and Saito, 2004, 2009; Bryck and Mayr, 2005; Saeki et al., 2006). Concurrently, they have to perform an articulatory suppression task, which may consist in reciting the days of the week or the months of the year (Baddeley et al., 2001), in saying "the" or "da" repeatedly (Baddeley et al., 2001; Saeki and Saito, 2004, 2009; Bryck and Mayr, 2005; Saeki et al., 2006), in saying the sequence "a–b–c" repeatedly (Emerson and Miyake, 2003) or in repeating "Tuesday" or "Thursday" (Miyake et al., 2004). Articulatory suppression is typically contrasted with a non-verbal secondary task, such as foot tapping, and with a control condition without any secondary task at all. Overall, data indicate that disrupting inner speech via articulatory suppression specifically impairs task-switching performance, above and beyond the detrimental effects imposed by the requirement to perform a dual task.

Articulatory suppression also makes it difficult to override prepotent responses. For instance, blocking inner speech ("inner voice") increases impulsive responding in a Go/No-Go task (Tullett and Inzlicht, 2010). Participants make more "Go" responses when they say the word "computer" repeatedly than when they continuously draw circles with their non-dominant hand. This is even more so in a switching version of the Go/No-Go task, which requires more self-control. As a consequence, Tullett and Inzlicht (2010) insist on the specific role that verbal resources play in self-control.

It is worth noting that research related to the interplay between language development and the development of action control also points in the same direction. More specifically, Karbach et al. (2011) demonstrated the positive influence of verbal relevant self-instructions for action-effect learning in 4-year-old children. In the same vein, Kray et al. (2008) provided evidence that the deficits in task-switching ability usually observed in younger children and older adults can be counteracted by verbal labelling. The action control benefits associated with verbalization appear to follow a U-shaped developmental trend across the lifespan.

Importantly, regardless of the apparent procedural differences and the specific goals of each study, the general conclusion arising from all these data is that disturbing inner speech has detrimental effects on executive control processes. In this light, inner speech thus serves as an internal self-cuing device that is particularly helpful when endogenous control is required. In other words, inner speech helps drive action in complex situations where information from the immediate past is needed. Building on this conclusion, the present study addresses the question of the relationship between consciousness and control by suppressing the possibility of exerting executive control on knowledge in implicit sequence learning.

Implicit sequence learning is the ability to learn sequential regularities without intending to learn (see Perruchet, 2008; Shanks, 2010). In a typical SRT task (Nissen and Bullemer, 1987), a visual target moves from location to location following a fixed sequence. The task is presented as a speed test in which participants have to track the target by pressing the corresponding keys as fast as possible. The absence of instructions regarding the existence of an underlying sequence makes it unlikely that participants develop any intention to learn its regularities. Nonetheless, they typically show increasing sensitivity to the sequential regularities contained in the sequence as training progresses, as demonstrated by gradually faster responses to predictable locations vs. novel locations (as when the training sequence is suddenly replaced by another). Under these circumstances, participants typically exhibit limited awareness of the sequential regularities (Cleeremans et al., 1998), and sequence learning therefore constitutes an excellent example of implicit learning. Here, at the end of the SRT task, people performed two forced-choice tasks, as in Destrebecqz and Cleeremans (2001). Participants first performed a generation task in which they had to freely generate a sequence under inclusion and exclusion instructions. In a final recognition task, participants were asked to react to old vs. new short sequences (triplets), and to decide, for each sequence, whether it had been presented before or not.

AIMS AND HYPOTHESIS OF THE PRESENT STUDY

The generation task is of particular interest here because it requires executive control. The specific version of the generation task we used here is based on Destrebecqz and Cleeremans (2001) and includes two phases. Participants first perform the generation task under inclusion instructions. They are asked to generate a sequence that resembles the training sequence as much as possible. Next, they perform the generation task under exclusion instructions, that is, they are asked to avoid reproducing the training sequence (that is, to generate a sequence that is as different as possible from the trained sequence). According to the Process Dissociation Procedure (Jacoby, 1991), generation under inclusion instructions constitute a facilitation task because both explicit and implicit knowledge may help participants generate the training sequence. In contrast, generation under exclusion instructions is an interference task because explicit and implicit knowledge of the repetitive pattern act in opposition: Only conscious, controlled knowledge can help participants avoid producing the training pattern. Thus, observing that fragments of the trained sequence are generated under exclusion instructions can only reflect lack of control.

Based on existing evidence that inner speech supports executive control processes, we assumed that it plays a specific self-cuing role in the generation task. Specifically, we assumed (based on informal interviews) that most participants verbally recode the material and use such verbal codes to organize their memory of the sequence and drive their generation responses, particularly under the difficult exclusion instructions. Thus, if this assumption is correct and that inner speech is indeed involved during generation, then blocking inner speech (through a concurrent articulatory suppression task) should make it particularly difficult for participants to override the tendency to generate training triplets under exclusion instructions. Articulatory suppression should not have such a strong influence under inclusion instructions, however, because generating the trained sequence can also be supported by implicit, automatic processes that do not depend so much on inner speech.

To sum up, the present study aims at disrupting executive control processes in the generation phase of an incidental sequence learning task. All participants were exposed in the same manner to the training sequence during the SRT task, and should thus all have learned the sequential regularities of the material to the same extent. They then performed the generation task (under both inclusion and exclusion instructions) in three different conditions: with concurrent articulatory suppression, with foot tapping, or without any secondary task. We predicted that articulatory suppression would specifically impair exclusion performance, in that participants should generate more elements from the training sequence in this condition, as compared to the control and foot tapping conditions. Finally, since all participants underwent the same recognition task as the final test of the study, we expected them to perform similarly in being able to differentiate between old and new sequential fragments. Observing a dissociation between generation and recognition performance in the articulatory suppression group would suggest that participants had acquired at least some conscious sequential knowledge but that they were nevertheless unable to exert control on it under exclusion instructions.

MATERIALS AND METHODS

PARTICIPANTS

Fifty-seven students aged 18–26 years from the Université Libre de Bruxelles received course-credits for taking part in the experiment. They were all unfamiliar with the SRT task. Nineteen of them were randomly assigned to each of three different conditions: articulatory suppression, foot tapping, and control. All participants had normal or corrected sight.

PROCEDURE AND MATERIAL

The experiment consisted in an SRT task, followed by the generation and recognition tasks. The SRT and recognition tasks were identical in all conditions, whereas the generation task differed according to the experimental conditions (articulatory suppression, foot tapping, and control). The display consisted of four dots arranged horizontally on the computer screen and separated by intervals of 3 cm. The stimulus was a small black circle 0.4 cm in diameter that appeared on a white background, centered 0.4 cm below one of the four dots. Each screen position corresponded to a key on the computer keyboard. The spatial configuration of the keys was fully compatible with the screen positions.

Participants performed a serial four-choice reaction time task during 15 training blocks of 96 trials, for a total of 1440 trials. On each trial, a stimulus appeared at one of the four possible screen locations. Participants were instructed to respond as fast and as accurately as possible by pressing on the corresponding key with the index and middle finger of each hand. Each block of trials began at a different point in the sequence. The target was removed as soon as a key had been pressed, and the next stimulus appeared after a 250 ms interval (i.e., RSI = 250 ms). Erroneous responses were signaled by means of a tone. Short rest breaks occurred between any two experimental blocks. Two second order conditional sequences (SOC1 = 342312143241 and SOC2 = 341243142132) were used in the SRT task. In each group, half of the subjects were trained on SOC1 during the first 13 blocks and during block 15; and on SOC2 during block 14 (that is, the transfer block). In this case, we will consider SOC1 as "own" sequence and SOC2 as "other" sequence. This design was reversed for the other half of the subjects. At the end of the SRT task, participants were informed that the dots had followed a repeating pattern. The two direct tests were then administered.

First, participants performed a generation task under inclusion and exclusion instructions (Destrebecqz and Cleeremans, 2001). A single stimulus appeared in a random location. Participants under inclusion instructions were required to generate a sequence that resembled the training sequence as much as possible. Subsequently, participants under exclusion instructions were required to generate another sequence (i.e., to try to avoid reproducing the sequential regularities of the training sequences). In both generation tasks, participants were also told not to repeat responses. The stimulus moved whenever participants had pressed one of the keys, and appeared at the corresponding location after a 250 ms RSI. In all conditions, a metronome was set to beat at the rate of 80 beats per min (i.e., one beat every 750 ms). Groups differed during the generation task: two groups of participants performed the task with a concurrent articulatory suppression or foot tapping secondary task, whereas the control group performed the generation task alone. The experimenter first described the secondary task and demonstrated how to perform it. Participants were instructed to say "ba-ba-ba" repeatedly once per metronome beat in the articulatory suppression condition, or to tap their dominant foot once per beat in the foot tapping condition. After receiving these instructions and watching the demonstration, participants practiced the secondary task to ensure that the task requirements were clear and that they could perform the task correctly. Then they performed the generation task (both under inclusion and exclusion instructions) in combination with the appropriate secondary task. Performance in the foot tapping and articulatory suppression tasks was closely monitored by the experimenter, who reminded the participants to keep up with the metronome when necessary. The procedure for the control condition was the same as that used for the two secondary task conditions, except that there was no secondary task to perform concurrently with the generation task. The metronome was nevertheless operating in this condition so as to equate the level of external noise to that in the two dual-task conditions. Generation scores were computed as the number of "own", "other," and "neither" triplets generated under inclusion and exclusion instructions separately. An "own" triplet is a triplet that was part of the training sequence; an "other" triplet is a triplet that was part of the transfer sequence; a "neither" triplet is a triplet that was neither "own" nor "other". The maximum number of "own" or "other" triplets was 96.

Finally, participants performed a triplets recognition task, as in Shanks and Johnstone (1999). Participants reacted to

24 fragments of three trials. Twelve were part of SOC1 and 12 were part of SOC2. Participants were asked to respond to stimuli as in the SRT task, and then to provide a rating of how confident they were that the fragment was part of the training sequence. Ratings involved a six points scale where 1 = "I am certain that this fragment was part of the training sequence" and 6 = "I am certain that this fragment was not part of the training sequence". It was emphasized to participants that they had to respond as fast as possible to the stimuli. Both ratings and reaction times were recorded.

RESULTS

Prior to each analysis of variance (ANOVA), data were tested with Mauchly's test of sphericity. Where sphericity was of concern, the degrees of freedom were modified with the Greenhouse-Geisser epsilon and effects are reported significant according to the adjusted alpha level. The data from one participant in the articulatory suppression condition was discarded because he did not follow the instructions in the generation task.

SERIAL REACTION TIME TASK

Participants trained with SOC1 and SOC2 were combined in all analyses. RT analyses were conducted for correct responses across 15 blocks. RTs associated with the first two stimuli of each block were excluded, because their locations could not be predicted. Mean error rate was very low (less than 5% of the trials) and did not vary between conditions ($F < 1, p > 0.5$). Errors are not discussed further.

Figure 1 shows the average RTs obtained over the entire experiment, plotted separately for the three generation conditions (as a reminder, all participants performed the SRT task under the exact same conditions). A first ANOVA with blocks 1–13 as a within-subjects variable and condition (articulatory suppression, foot tapping, and control) as a between-subjects variable only revealed a significant effect of block, [$F_{(4.83,\ 256.22)} = 15.99$, $p < 0.001$, $\eta_p^2 = 0.23$]. There was no effect of condition, and no blocks × condition interaction ($Fs < 1$, $ps > 0.5$). As can be seen on **Figure 1**, this suggests that the overall RTs decrease with practice—from 461.25 ms ($SD = 88.67$) in the first six blocks down to 432.99 ms ($SD = 78.61$) in the last seven blocks. As expected, this decrease does not differ between groups. More importantly, the transfer effect, as induced by the presentation of a different sequence on block 14, gives an indirect index of sequence learning. An ANOVA with transfer (block 14 vs. the mean of blocks 13 and 15) as within-subjects variable and condition (articulatory suppression, foot tapping, and control) as between-subjects variable yielded a significant effect of transfer, [$F_{(1,\ 53)} = 151.97$, $p < 0.001$, $\eta_p^2 = 0.74$]. Overall, reaction times increased by 65.86 ms ($SD = 5.29$) when the training (own) sequence was changed to another sequence in block 14. As in the previous analysis and as expected, there was no effect of condition, and no transfer × condition interaction ($Fs < 1$, $ps > 0.4$).

This suggests (1) that RTs increased significantly in the three conditions when the sequence was modified and (2) that this RTs increase was of same extent in all three conditions, suggesting equivalent levels of sequence learning. Taken together,

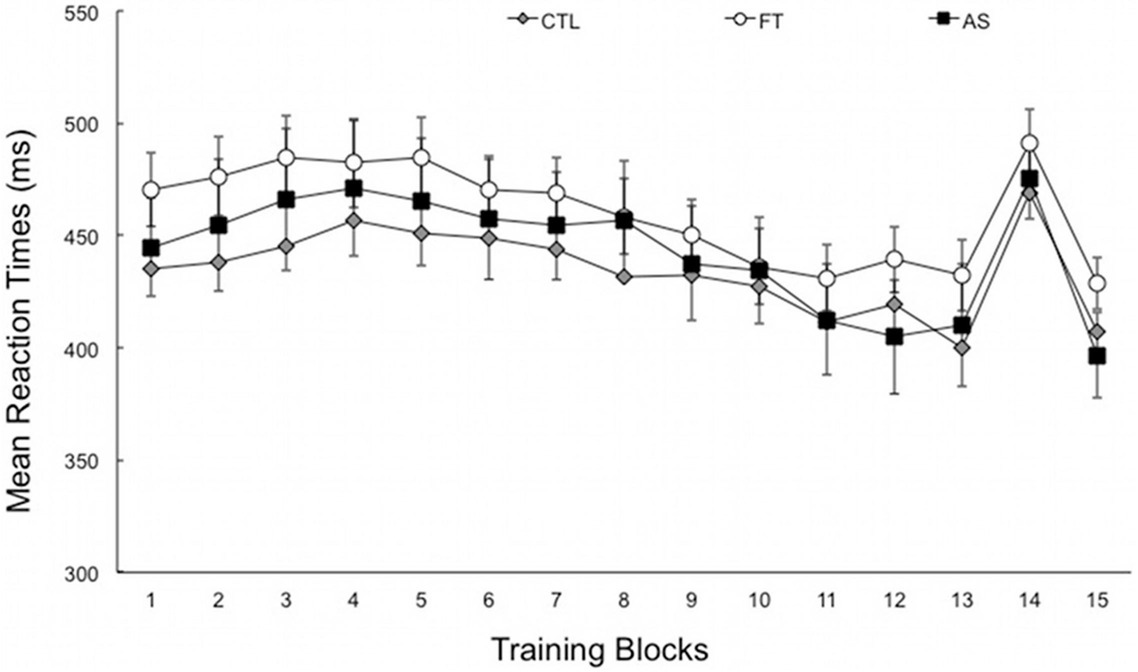

FIGURE 1 | Mean reaction times for each training block, plotted separately for the three conditions: articulatory suppression (AS), foot tapping (FT), and control (CTL) groups. Block 14 corresponds to the transfer block. Recall that the experimental setting did not differ during SRT task (data are plotted separately for clarity). Error bars represent standard errors.

SRT task results show that sequence learning was observed in the three groups of participants. Indeed, the RTs decreased with practice when the same sequence is presented to the participants, increased when the sequence was modified and decreased again when the training sequence was put anew. We now examine whether participants differ in their ability to project their knowledge of the sequence in generation and recognition tasks.

GENERATION TASK

Figures 2A,B show the mean number of "own", "other," and "neither" triplets generated under inclusion and exclusion instructions, respectively. "Neither" triplets will not be considered since the focus of interest lies in the comparison between "own" and "other" triplets.

We first compared the number of "own" triplets (from the training sequence) generated under inclusion and exclusion instructions in the three conditions. An ANOVA with instructions (inclusion vs. exclusion) as a within-subjects variable and conditions (articulatory suppression, foot tapping, and control) as a between-subjects variable revealed a significant instruction effect, [$F_{(1,\ 53)} = 11.67$, $p = 0.001$, $\eta_p^2 = 0.18$], indicating that overall participants generated more "own" triplets in inclusion than in exclusion ($M = 43.05$, $SD = 11.58$ and $M = 33.55$, $SD = 13.39$, respectively). The main effect of condition was marginally significant, [$F_{(2,\ 53)} = 3.08$, $p = 0.054$, $\eta_p^2 = 0.10$], suggesting that the overall number of triplets generated varied across conditions ($M = 38.66$, $SD = 6.41$ in the control condition, $M = 35.72$, $SD = 8.23$ in the foot tapping condition, and $M = 42.22$, $SD = 9.15$ in the articulatory suppression condition). The instruction × condition interaction failed to reach significance, [$F_{(2,\ 53)} = 1.93$, $p = 0.16$, $\eta_p^2 = 0.07$]. However, the pattern of results indicates that more "own" triplets were generated under exclusion instructions in the articulatory suppression group only. Considering that we had a strong *a priori* hypothesis regarding the effect of articulatory suppression on exclusion performance, and that the F-value of the interaction was above 1 (see Wilcox, 1987 for details), we carried out planned contrasts on the mean number of "own" triplets generated under inclusion and exclusion instructions separately. As expected, inclusion performance in the articulatory suppression group did not differ from the other groups, $t(53) = 0.61$, $p > 0.50$. In contrast, and crucially for the purpose of the present study, participants in the articulatory suppression condition generated significantly more "own" triplets in exclusion than participants in the control and foot tapping conditions ($M = 40.01$, $SD = 3.20$ for articulatory suppression condition vs. $M = 31.95$, $SD = 2.05$ for control and foot tapping conditions taken together), $t(53) = 2.17$, $p < 0.05$.

Additional paired-samples t-tests compared the number of "own" and "other" triplets generated under inclusion and exclusion instructions for each of the three groups, hence providing an appropriate chance level[1]. Participants generated significantly more "own" than "other" triplets under inclusion instructions in

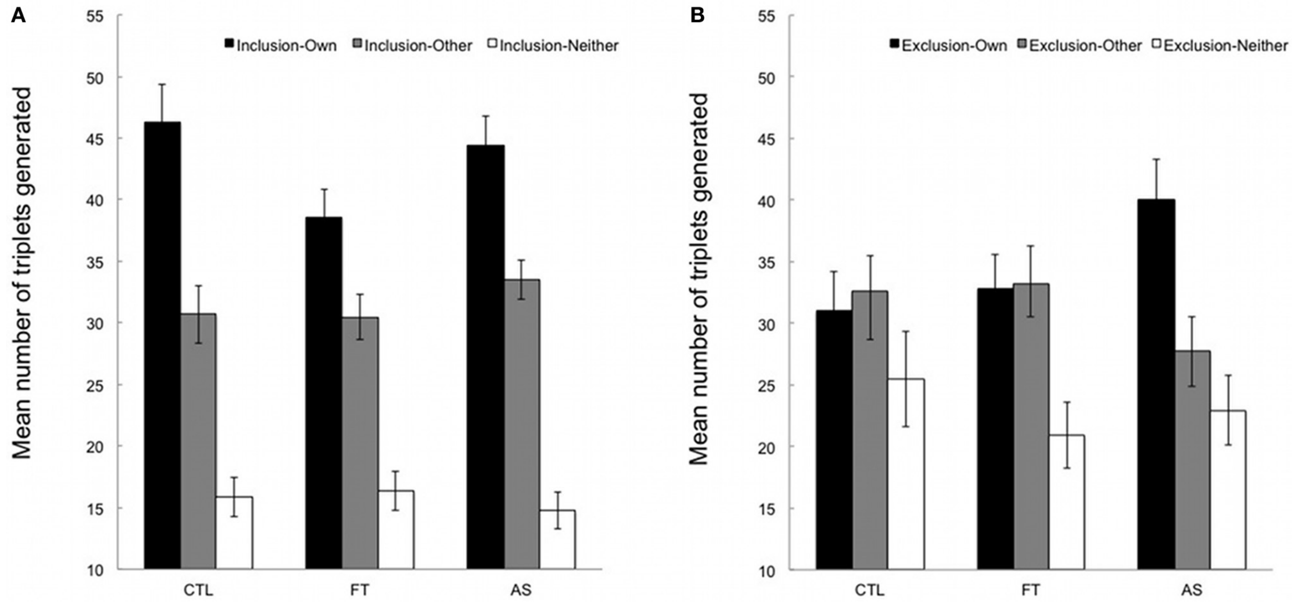

FIGURE 2 | (A) Mean number of triplets generated in inclusion under articulatory suppression (AS), foot tapping (FT), and control (CTL) conditions. "Own", number of SOC triplets generated from the training sequence; "other", number of triplets from the alternate, untrained sequence; neither, number of triplets from neither the training nor the untrained sequence. Error bars represent standard errors. **(B)** Mean number of triplets generated in exclusion under articulatory suppression (AS), foot tapping (FT), and control (CTL) conditions. "Own", number of SOC triplets generated from the training sequence; "other", number of triplets from the alternate, untrained sequence; neither, number of triplets from neither the training nor the untrained sequence. Error bars represent standard errors.

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[1] The appropriate baseline level of performance in the generation task consists in the comparison between "own" and "other" triplets. Indeed, the alternative "other" sequence is structurally identical to the training "own" sequence, except that the former was trained and the latter was not (Wilkinson and Shanks, 2004).

all groups, $t(18) = 2.95$, $p < 0.01$, $t(18) = 2.97$, $p < 0.01$, and $t(17) = 2.92$, $p = 0.01$ in the control, foot tapping, and articulatory suppression, respectively. Thus, participants demonstrated above-baseline sequence knowledge in the inclusion task, irrespective of whether they had to perform a concurrent secondary task or not, and irrespective of the nature of the secondary task. A different pattern of results emerges under exclusion instructions. While a similar number of “own” and “other” triplet was generated both in the control and foot tapping conditions, all $ts < |1|$, $ps > 0.70$, participants generated significantly more “own” than “other” triplets ($M = 40.01$, $SD = 3.20$ vs. $M = 27.72$, $SD = 2.77$) in the articulatory suppression condition, $t(17) = 2.33$, $p < 0.05$. This suggests that participants were specifically unable to withhold their responses during the exclusion task when an articulatory suppression task had to be performed concurrently.

Taken together, our data suggest that the acquired sequential knowledge was available in a direct generation test. Above-chance inclusion scores in all conditions indicate that participants were able to recruit this knowledge when necessary. In exclusion, participants demonstrated some level of control over the expression of their knowledge, not only when they performed the task alone in the control condition, but also when a concurrent foot-tapping task was added. Conversely, and as predicted, a detrimental effect of articulatory suppression was observed, above and beyond the costs associated with the requirement of performing two tasks at the same time.

RECOGNITION TASK

Participants were required to react to sequences of three elements (triplets) by pressing the key corresponding to the location of the stimulus (as in the SRT task) and to rate from 1 to 6 the extent to which they felt these sequences were old or new (i.e., “own” vs. “other”). Sequences with erroneous responses were excluded. Mean recognition ratings for both types of sequence (“own” vs. “other”) are plotted separately for the three conditions. High ratings correspond to judgments of novelty and are expected for “other” triplets, whereas low ratings correspond to judgements of oldness and are expected for “own” triplets.

As can be seen in **Figure 3**, “own” and “other” triplets are overall correctly discriminated. An ANOVA with type of sequence (“own” vs. “other”) as within-subjects variable and condition (articulatory suppression, foot tapping, and control) as between-subjects variables yielded a significant main effect of type only, $[F_{(1,\,53)} = 26.36, p < 0.001, \eta_p^2 = 0.33]$. Neither the main effect of condition, nor the type × condition interaction reached significance, $F < 1$ and $[F_{(2,\,53)} = 1.23, p = 0.28, \eta_p^2 = 0.05$, respectively]. Overall this indicates that participants were able to differentiate between “own” and “other” triplets ($M = 2.95$, $SD = 0.51$ and $M = 3.36$, $SD = 0.57$). More importantly, this ability to recognize parts of the training sequence did not differ across conditions.

DISCUSSION

Consider the familiar “Neither yes nor no” game, in which one is repeatedly asked “Yes/No” questions under the constraint that his/her answers should be neither “yes” nor “no”. Winning the game requires tight executive control as one has to continuously refrain from the strong, prepotent tendency to respond to the questions in the familiar manner, that is, by saying either “yes” or “no”. Inevitably, as attention wanes, one comes to the point where one answers “without thinking about it” by producing precisely the answer that had to be avoided. Should we therefore

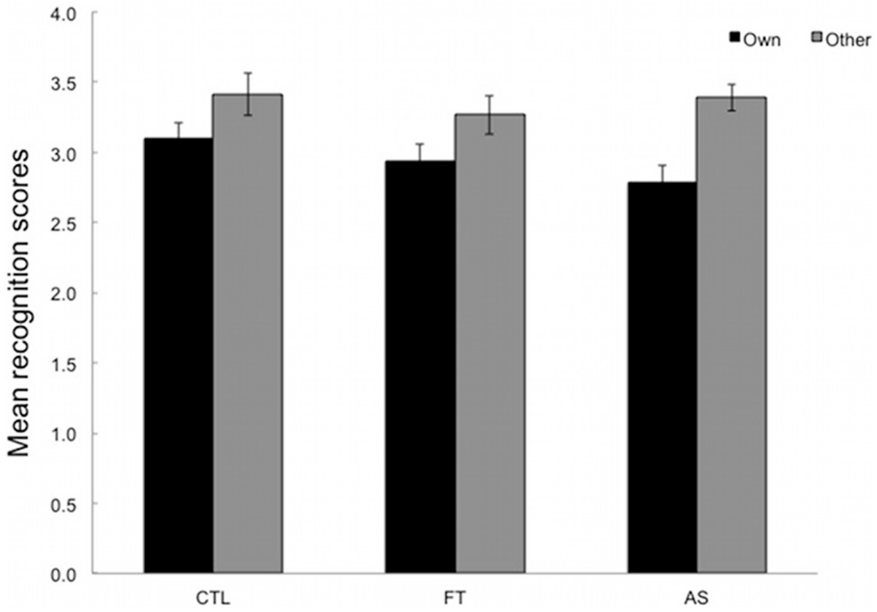

FIGURE 3 | Mean recognition ratings given for the 24 test triplets, plotted separately for the three conditions: articulatory suppression, foot tapping, and control. Low ratings (between 1 and 3) are expected for old (“own”) triplets whereas high ratings (between 4 and 6) are expected for new (“other”) triplets. Error bars represent standard errors.

consider this automatic, uncontrolled responding as inherently unconscious? We do not think so. Most people indeed realize that they failed the game immediately after having uttered the taboo words "yes" or "no" or even while uttering them: they blush, chuckle, say "oops," and so on. This indicates that they were perfectly aware of the inadequacy of their response, but just could not help it.

The "neither yes nor no" game is a good illustration of the phenomenon we sought to explore with this study. Participants were first incidentally trained to become sensitive to sequential regularities in a SRT task. In a subsequent generation task, they were then asked to generate these sequential regularities under inclusion instructions, that is, under conditions where both automatic and controlled processes contribute to increasing performance. Next, participants had to carry out the same generation task, but this time under exclusion instructions, that is, under instructions to specifically avoid producing the learned sequential regularities. In other words, the prepotent tendency to reproduce what they had been trained on now had to be suppressed, just as a "yes" or "no" response has to be withheld in the game. Under such exclusion instructions, automatic and controlled processes thus act in opposition, for expressing automatic knowledge cannot be refrained. In the final recognition task participants had to discriminate between fragments that were part of the training sequence or not. They were required to express their knowledge of the sequence through a continuous scale, with build-in confidence judgements.

Thus, the generation task under exclusion instructions and the recognition task can be conceived as reflecting different aspects of our ability to use knowledge: Exclusion task performance provides an index of the extent to which such knowledge can be controlled, while recognition task performance provides and index of the extent to which this knowledge is consciously accessible (see Gaillard et al., 2009 for a similar reasoning in aging, but see Rünger and Frensch, 2010 for a critique of the use of direct tests to measure consciousness). Any dissociation between performance in the exclusion subtask and in the recognition task would therefore demonstrate the absence of a systematic association between control and consciousness. Such a dissociation is exactly what we observed when participants performed the generation task without the possibility to rely on inner speech to help inhibiting sequential fragments in the exclusion subtask.

Blocking inner speech thus increased impulsive responding as in the Go/No-Go task (Tullett and Inzlicht, 2010). That is, participants in the articulatory suppression group were not able to withhold the tendency to reproduce the training sequence under exclusion instructions, whereas participants in the control and foot tapping groups demonstrated that ability. One might argue that those between-group differences may be due to pre-existing differences in a number of basic cognitive abilities, such as fluid intelligence or working memory. However, such differences have little bearing on implicit learning (Feldman et al., 1995; Unsworth and Engle, 2005; Kaufman et al., 2010). The influence of processing speed is less clear. On the one hand, Kaufman and colleagues (2010) observed a link between processing speed and implicit learning but they reckon that the nature of this link remains unclear. On the other hand, small to non-existent correlations have been shown between incidental learning measures and processing speed (Feldman et al., 1995). Thus we are rather confident that the specific difficulties observed in the exclusion performance with concurrent articulation suppression do not stem from any baseline group differences. Moreover and most crucially, this impaired performance cannot be explained either by insufficient knowledge of the sequence or by lack of conscious knowledge of the sequence. Indeed, participants in the articulatory suppression group did not differ from the other groups in the incidental learning phase. Under inclusion instructions, they also retrieved the appropriate sequential knowledge and produced sequential ("own") fragments similarly to control and foot tapping participants. In addition, they were able to make conscious (correct) decisions about the extent to which sequential fragments were familiar or not, just as other participants, in the recognition task. It is important to keep in mind that the recognition scores in our experiment did not only consist in judging whether a given triplet was part of the training sequence, as in Yes/No binary responses, but also required participants to indicate how confident they were in their judgment. Thus our data suggest that conscious access and executive control might not be always associated after all. This conclusion is very much in line with Tzelgov's (1997) theory of automaticity, in which automaticity is characterized not by the fact that it involves unconscious knowledge, but rather by the fact that behavior guided by automatic knowledge has a ballistic character, that is, that once initiated, it unfolds of its own until the learned effect is obtained. Thus, according to Tzelgov, we are (at least potentially) aware of most automatic behavior—it is just that such behavior can no longer be the object of executive control.

Our results are also consistent with Cleeremans' theory of automaticity (Cleeremans, 2008), according to which both executive control and availability to consciousness depend on representation quality, where quality involves graded dimensions such as strength, stability in time, and distinctiveness, all driven by learning mechanisms the computational objective of which is to increase overall adaptation. Weak representations, typical of implicit cognition (e.g., subliminal perception) are of poor quality and hence are only weakly available to conscious awareness. Such representations also do not require conscious control for they only exert weak effects on behavior. Very strong representations, on the other hand, are characteristic of automaticity, and likewise do not require cognitive control in virtue of the fact that they are adapted. The strength of such representations makes them available to conscious awareness in a manner that the weak representations characteristic of implicit cognition cannot achieve. Thus, with automatic behavior, consciousness has become optional: The knowledge is available to conscious inspection, but such conscious monitoring is not necessary for the knowledge to drive behavior in an adapted manner. Note, however, that such adaptation can fail. For instance, it is almost impossible for a continental pedestrian not to turn his head leftwards when crossing a street in London, for the learned behavior is so automatic that it can only be prevented from being triggered by environmental cues with considerable effort. Likewise, the ironic instruction "Do not think of a white bear" (Wegner et al., 1987) is almost impossible to follow. It should be clear that these examples of maladaptive automated behavior are the exception rather than the rule, however. It is also striking to note that in all such cases, one is acutely aware of the existence of a conflict and of our inability to overcome it.

Congruently, our data suggests that knowledge that cannot be controlled is available to awareness. It is interesting to reflect upon other possible patterns of dissociation between executive control and conscious awareness. In particular, one may wonder whether full control is possible in the absence of awareness. Intuitively, this should be possible, since after all, it is precisely what happens when we are behaving automatically. This pattern of dissociation is what Dienes and Perner (2007) described as involving "COLD control", that is, as involving executive control without higher-order thought (HOT, Rosenthal, 1997). In the cold control theory of hypnosis, Dienes and Perner argue that hypnosis offers promising ways to study executive control without conscious awareness. For instance, they report an experiment in which participants counted six fingers on their hand, after they received the hypnotic suggestion to forget the number "4". Overriding the tendency to count "1, 2, 3, 4, 5" fingers on a hand requires executive control and yet, participants deny awareness of why they counted six fingers on their hand.

What distinguishes our approach of the consciousness-control problem from the cold control perspective is that our participants were all fully aware during the experiment, (i.e., they were not in any modified state of consciousness). Moreover, all our stimuli were supraliminal, as opposed to studies exploring the relationship between consciousness and control with subliminal stimuli (Heinemann et al., 2009; van Gaal et al., 2009; Kiefer and Martens, 2010; Capa et al., 2011). However, some of them could not recruit inner speech as self-cuing aid during the generation task. This resulted in a specific detrimental effect of articulatory suppression, (i.e., concurrent foot tapping did not result in less control over the sequence under exclusion instructions). This is reminiscent of previous data obtained with the task-switching paradigm (Emerson and Miyake, 2003; Miyake et al., 2004; Saeki and Saito, 2004, 2009; Bryck and Mayr, 2005; Saeki et al., 2006). The involvement of inner speech in cognitive control is further suggested by the relationship between inner speech production and increased activity in the left inferior frontal gyrus (LIFG), which is similarly recruited during working memory tasks (see Morin, 2009).

Thus our results clearly suggest that inner speech plays an important role in the recall and control of implicitly acquired sequence knowledge. To the best of our knowledge, only one study investigated the role of inner speech in sequence learning (Farley et al., 2007, Exp. 3–4). However, Farley and colleagues intended to disrupt sequence learning itself (and not the product of learning, i.e., sequential representations) with irrelevant speech, on the ground that irrelevant speech is detrimental to serial order processing. Irrelevant speech lengthened reaction times in the SRT task, but did not prevent learning of the sequence. This is further evidence that the role inner speech plays is a specific one. Blocking inner speech is not detrimental to automatic tasks such as sequence learning but it impairs performance in tasks requiring endogenous control, as the generation-exclusion subtask.

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Age-related deficits in efficiency of low-level lateral inhibition

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Background: In a masked prime task using a 0 ms prime-target inter-stimulus-interval, responses on trials where prime and target match (compatible trials) are usually faster and more accurate than responses where prime and target mismatch (incompatible trials). This positive compatibility effect (PCE) comprises both behavioral benefits on compatible relative to neutral trials, and behavioral costs on incompatible relative to neutral trials. Comparing performance in 2- vs. 4-alternative-response versions of the task indicates that benefits are due to direct priming (i.e., pre-activation) of a motor response, whereas costs reflect an inhibition of the alternative response tendency. The present study employs this paradigm to test the hypothesis that normal aging is associated with a selective deficit in inhibitory function, affecting both low-level motor and higher-level executive control. **Experiment and Results:** Testing 20 young and 20 older healthy adults, we found that (1) overall, prime-induced benefits were of similar magnitude across age groups, but inhibition-based costs were smaller in older compared to young adults; (2) increasing the number of response alternatives caused the same pattern of unaltered benefits and reduced costs in both age groups; and (3) costs, but not benefits, in the 2-alternative condition were significantly predicted by scores on the digit symbol substitution task (DSST), independently of age and other background variables. **Interpretation:** Results demonstrate the possibility of isolating an inhibitory component in low-level perceptuo-motor control. Importantly, this component shows an age-related decline in the absence of a corresponding decline of visuo-motor excitability, and appears to be linked to performance on a higher-level processing speed task. We hypothesize that aging might affect the brain's ability to establish precise short-term lateral inhibitory links, and that even in young adults, the efficiency of such links is a significant contributing factor in higher-level cognitive performance.

Keywords: aging, inhibition, motor control, positive compatibility effect, masked priming

Normal aging is typically accompanied by a decline in many cognitive and motor functions. An increasing body of evidence suggests that both a general slowing of processing speed and dysregulation in specific brain regions—particularly the frontal lobes—contribute to this decline (e.g., Bugg et al., 2006). In line with this, an influential model of cognitive aging proposes that reduced inhibitory control, resulting in increased distractibility, is one of the main factors of age-related cognitive decline (Hasher et al., 1999). However, "inhibition" refers not to a specific phenomenon, but to a variety of cognitive functions and processes, each of which might be differently affected by aging (e.g., Kramer et al., 1994; Nigg, 2000; Andres et al., 2008; Collette et al., 2009; Verhaeghen, 2011). Correspondingly, evidence for age-related inhibitory deficits have been observed in some studies, but not in others, depending on the type of inhibition under investigation (see Maylor et al., 2005, for examples). Furthermore, even a seemingly unitary inhibitory process like the suppression of a motor response might show divergent patterns of results, depending on the tasks employed to test it. For instance, investigating response suppression in a Simon and in a priming task, Burle et al. (2005) obtained positively correlated results, suggesting a common underlying mechanism. In contrast, Swick et al. (2011) found that response suppression in a go/nogo and in a stop-signal task relied on only partially overlapping cortical and subcortical structures, suggesting distinct underlying mechanisms.

If even an apparently specific instantiation of inhibition like response suppression might potentially involve various (sub-) processes, each of which might or might not be affected by aging, then it seems advisable to investigate age-related inhibitory deficits using a narrowly defined, highly specific type of inhibition. The present study used the inhibitory component of masked prime-induced motor activation for this purpose.

MOTOR ACTIVATION AND INHIBITION IN THE MASKED PRIME PARADIGM

The masked prime paradigm is an experimental procedure aimed at investigating low-level, automatic visuo-motor control processes (e.g., Eimer and Schlaghecken, 1998). In this task, participants give a speeded motor response to a simple visual target (e.g., a left-hand key-press to an arrow pointing to the left). Each target is preceded by a prime stimulus, which is associated with either the same response as the subsequent target (compatible trial), with a different response (incompatible trial), or is without response assignment (neutral trial). Primes are presented very briefly (e.g., 33 ms) and are followed by a patterned backward mask. This makes them unlikely to be perceived consciously (near-threshold or subthreshold presentation), as evidenced by participants' informal verbal reports and by their inability to identify primes with more than chance accuracy (Schlaghecken and Eimer, 1997; Eimer and Schlaghecken, 1998, 2002). Yet these primes can be shown to trigger their corresponding motor activation, thereby influencing responses to the subsequently presented, clearly visible targets.

The priming effects typically present a biphasic pattern (e.g., Aron et al., 2003; Seiss and Praamstra, 2004; Schlaghecken and Maylor, 2005; Sumner and Brandwood, 2008): when prime and target are presented in immediate succession, responses are faster and more accurate on compatible than on incompatible trials (positive compatibility effect, PCE); if target presentation is slightly delayed (by about 100–250 ms), the priming effect reverses (negative compatibility effect, NCE), a pattern indicative of an activation-followed-by-inhibition sequence. Interestingly, it has been found that in healthy older participants, the initial PCE is of approximately the same magnitude as in young participants, whereas the subsequent NCE is much reduced or even absent (e.g., Seiss and Praamstra, 2004; Schlaghecken and Maylor, 2005; Schlaghecken et al., 2011), suggesting that motor inhibition, but not prime-induced motor activation, deteriorates with old age. In contrast to these results, however, Sumner et al. (2007) observed robust NCEs in older participants, suggesting intact motor inhibition. In fact, an analysis of the priming effects of 80 older adults revealed large individual differences in the NCE latency range, with some participants producing "normal" NCEs, but others showing PCEs (Schlaghecken et al., 2011). In that study, no predictor for these differences could be identified. However, it seems likely that the NCE reflects the combined activity of more than one inhibitory process (see, e.g., McBride et al., 2012, for a review), complicating the pattern of deteriorating and spared functions. Thus, it might be interesting to employ a simpler measure of low-level motor inhibition to investigate age-related and individual differences in motor control.

In the typical 2-alternative choice reaction time (RT) task, the PCE comprises behavioral benefits (improved performance on compatible relative to neutral trials) and costs (impaired performance on incompatible relative to neutral trials) of approximately equal magnitude (Aron et al., 2003; Schlaghecken et al., 2006). These effects are generally assumed to reflect activation and inhibition processes in the visuo-motor system (rather than, for instance, processes of perceptual or attentional modulation, e.g., Schlaghecken and Eimer, 2001; Boy and Sumner, 2010). That is, the masked prime is assumed to directly activate its corresponding motor response (e.g., Neumann and Klotz, 1994; Kiesel et al., 2007), resulting in performance benefits when the target requires execution of this same response (compatible trial). Importantly, it is further assumed that the activity level of one visuo-motor channel systematically affects activity in competing channels via reciprocal inhibitory links. Thus, once the prime has activated its corresponding motor response, this increased activity in one channel will cause a corresponding decrease of activity in the alternative response channel, resulting in behavioral costs when the target requires execution of this inhibited response (incompatible trial).

The feasibility of separating direct prime activation and indirect competitor inhibition has been demonstrated in a masked prime experiment where responses had to be given by moving a finger from a central "home" location to one of two or four target locations (Schlaghecken et al., 2006). The logic behind this manipulation was as follows: (1) if masked priming effects are located at the level of motor response codes (rather than either at abstract "left" or "right" codes or at specific muscle commands; see Eimer et al., 2002; Schlaghecken et al., 2009), then they should be unaffected by the type or number of effectors, that is, a single-effector choice RT paradigm should yield the same effects as a two-effector choice RT paradigm; (2) if behavioral benefits on compatible relative to neutral trials reflect a direct ("local") activational effect of the prime, then benefits should remain unaffected by the number of response alternatives; and (3) if behavioral costs on incompatible relative to neutral trials reflect indirect ("global") inhibition of alternative response channels via reciprocal inhibitory links, then costs should decrease with increasing numbers of channels participating in this inhibitory network. Schlaghecken et al. (2006) obtained results exactly in line with these predictions: whereas benefits were virtually identical in the 2- and the 4-alternative condition (9.4 and 9.3 ms), costs were substantially reduced (from 14.2 to 4.6 ms) with the increased number of response alternatives, confirming that direct activation and reciprocal competitor inhibition processes can be successfully dissociated in the masked prime task, even when different responses are given with the same effector.

RECIPROCAL INHIBITION AND AGING

Reciprocal inhibitory links appear to be an inherent feature of the perceptuo-motor system, such that activation of one response channel causes a corresponding inhibition of its competing response channel(s) (e.g., Duque et al., 2010; Tandonnet et al., 2011; for a review, see, e.g., Burle et al., 2004). This competitor inhibition is established in a task-dependent manner, not merely through reciprocal inhibition of homologous cortical structures (e.g., Meynier et al., 2009), and might critically depend on pre-supplementary motor area (pre-SMA) circuits (for a review, see Mostofsky and Simmonds, 2008)[1]. Note that this type of inhibition differs from top-down, frontally mediated inhibitory control: it is not the (voluntary) suppression of an incorrect response tendency, but the automatic, feed-forward fine-tuning of the desired response through the suppression of any competing motor activity.

Of particular interest in the present context is the finding that reciprocal inhibition appears to deteriorate with age. This has been demonstrated for both intra-hemispheric (Hortobágyi et al., 2006) and inter-hemispheric (Talelli et al., 2008) task-specific

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[1] It might be interesting to note that Sumner et al. (2007) found evidence that pre-SMA also plays a role in generating the second, NCE phase of masked prime effects.

inhibition during single responses. Furthermore, van de Laar et al. (2012) have suggested that the same might be true for choice (between-hand) reactions. However, inhibitory links and their age-related changes in the intermediate condition—a choice RT task employing a single-effector—have, to the best of our knowledge, not as yet been investigated. Finding age-related changes in motor inhibition in such a paradigm would demonstrate that aging does indeed affect *ad-hoc*, task-related perceptuo-motor links, not just anatomical links between antagonistic muscle pairs or homologous motor cortex areas.

The present study, therefore, employed the paradigm used in Schlaghecken et al. (2006), where single finger movements were mapped onto different targets under 2- and 4-alternative response conditions. We compared performance of young and older participants in this paradigm, aiming to replicate and extend the earlier findings by separating the effects of aging on direct motor activation and on reciprocal motor inhibition.

AGING, INHIBITION, AND PROCESSING SPEED

It is generally agreed that the speed of information processing decreases with increasing age (e.g., Salthouse, 1996, 2004). This is likely due to a combination of reduced nerve conduction velocity (e.g., Stetson et al., 1992) and age-related loss of synaptic connections (e.g., Fjell and Walhovd, 2010), resulting in an overall deterioration of functional neural networks (e.g., Andrews-Hanna et al., 2007; Damoiseaux et al., 2008) and a corresponding deficiency in the formation of neural representations (e.g., Rousselet et al., 2009).

A typical measure of processing speed in many aging studies is the digit symbol substitution task (DSST; see Hoyer et al., 2004). As a subtest of Wechsler intelligence scales, the DSST correlates highly with intelligence and is generally acknowledged to involve higher levels of cognition than simply perceptual speed (e.g., Laux and Lane, 1985; Piccinin and Rabbitt, 1999; Gilmore et al., 2006), possibly including inhibitory processes. Lustig et al. (2006), comparing young and older adults' performance under low- and high-distraction conditions, found that the ability to ignore distracting information is an important factor in DSST and DSST-like measures of processing speed. However, as the authors point out, being able to ignore distractors is not entirely determined by inhibitory control: factors such as visual acuity and gaze control might also play a role. To the best of our knowledge, there has as yet been no study to directly relate processing speed to low-level inhibitory control. Because the present study has been designed to obtain a relatively pure measure of low-level inhibition (behavioral costs on incompatible relative to neutral trials in the 2-alternative version of the masked prime task), it is suitable to address this issue.

METHODS

PARTICIPANTS

Twenty young (seven male) and 20 older (nine male) healthy participants completed the experiment (see **Table 1** for details). Young participants (aged 18–33) were mostly students at the University of Warwick who took part either for course credit or for payment of £6. Older participants (aged 63–81) were members of a volunteer panel who had been recruited through local newspapers and advertisements to join the Warwick Age Study and were paid £10 as a contribution toward their travel expenses. All but one young and two older participants were right handed.

BACKGROUND MEASURES

Crystallized intelligence was assessed by the multiple choice section of the Mill Hill vocabulary test (Raven et al., 1988), in which participants have to select the best synonym for a target word from a set of six alternatives. Speed of information processing was assessed by the DSST from the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981). Visual acuity was assessed (with glasses if worn) at the beginning of the experiment using the Near Vision Test Card (Schneider, 2002). All participants had normal or corrected-to-normal vision according to self-report. The data in **Table 1** show the typical pattern reported in the aging literature (e.g., Baltes and Lindenberger, 1997; Schneider and Pichora-Fuller, 2000) of higher processing speed and visual acuity, but lower crystallized intelligence, in young compared with older adults. Moreover, the DSST means correspond almost exactly with those reported for 20- vs. 70-year-olds (70 vs. 49, respectively) in a meta-analysis of 141 studies by Hoyer et al. (2004), again suggesting that the present samples are representative of their age group.

STIMULI AND APPARATUS

Double arrows pointing left, right, up, or down served as primes and targets, and a double plus sign served as an additional neutral prime (see **Figure 1**). Stimuli subtended a visual angle of 1.2° × 0.6° at a viewing distance of approximately 1 m. Masks were constructed from a virtual 8 × 6 grid (2.3° × 1.4°), randomly filled with overlapping horizontal, vertical, and oblique

Table 1 | Background details (means and standard deviations) of young and older participants, and results of comparisons between age groups.

Variable	Young	Older	
	M (SD)	M (SD)	Comparison
Age (years)	22.3 (4.3)	70.3 (5.3)	–
Health[a]	4.7 (0.5)	4.1 (0.6)	$t_{(34)} = 3.23, p < 0.01$
Vocabulary[b]	18.5 (4.0)	23.2 (2.8)	$t_{(36)} = -4.23, p < 0.001$
Speed[c]	70.1 (14.9)	50.8 (10.4)	$t_{(36)} = 4.67, p < 0.001$
Visual acuity[d]	7.0 (1.1)	5.1 (1.3)	$t_{(38)} = 5.06, p < 0.001$

[a] *Self-rated health on a 5-point scale (very poor; poor; fair; good; very good); data missing for two young and two older participants.*

[b] *Vocabulary from the multiple choice section of the Mill Hill vocabulary test (Raven et al., 1988); maximum score = 33; data missing for two young participants.*

[c] *Processing speed based on the Digit Symbol Substitution task (Wechsler, 1981); data missing for two young participants.*

[d] *Visual acuity as measured by the number of lines read correctly from the Near Vision Test Card (Schneider, 2002) viewed at a distance of 16 inches whilst wearing corrective glasses, with scores ranging from 1 (16/160—lowest acuity) to 9 (16/16—highest acuity).*

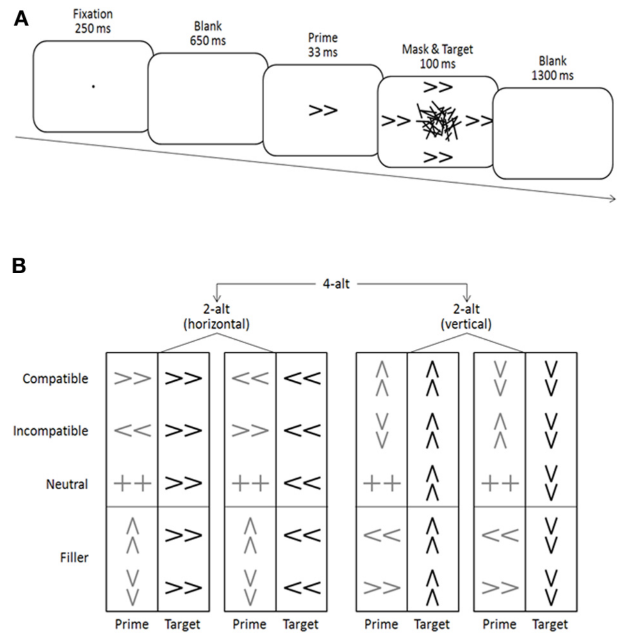

FIGURE 1 | (A) Schematic illustration of a (compatible) trial. **(B)** List of all possible trials in the two 2-alternative (2-alt) choice tasks and the combined 4-alternative (4-alt) choice task.

lines of different lengths (0.1°–1.0°; width 0.2°). A new mask was constructed on each trial to avoid perceptual learning of the mask and correspondingly increased prime identification (see Schubö et al., 2001; Schlaghecken et al., 2008). Stimuli were presented in black on a white background on a 17″ computer screen. A fixation dot (0.1° × 0.1° visual angle), primes and masks appeared in the center of the screen, whereas targets appeared 2.0° above, below, to the left and to the right of the center (i.e., just beyond the area occupied by the mask—see **Figure 1A**). Participants were seated in a comfortable chair in a dimly lit, sound attenuated chamber approximately 1 m in front of a computer screen. They pressed the "2," "4," "6," or "8" key on the number pad of a standard keyboard in response to the corresponding target direction (down, left, right, and up, respectively).

PROCEDURE

In experimental sessions lasting up to 1 h, participants first carried out eight blocks of the 2-alternative choice RT task (2-alt), then eight blocks of the 4-alternative choice RT task (4-alt). Immediately after the experiment, background cognitive measures were collected from young participants (this information was already available for older participants from an earlier experiment).

A typical trial sequence is depicted in **Figure 1A**. Trials started with a fixation cross presented for 250 ms, followed by a 650 ms blank screen. A prime was then presented for 33 ms, replaced immediately by a 100 ms mask surrounded by four identical targets. The inter-trial interval between target offset and the next fixation dot was 1300 ms. On compatible trials, prime and target arrows pointed in the same direction, on incompatible trials, they pointed in opposite directions (e.g., left-pointing prime, right-pointing target), and on neutral trials, the prime was a double-plus sign not associated with any response. Trials where prime direction was orthogonal to target direction (e.g., left-pointing prime, upward-pointing target) were considered as filler trials, and were not part of the main analysis.

Participants were instructed to maintain central eye fixation, and to respond as quickly and accurately as possible to the direction of the target arrows by moving the index finger of the right hand from its resting position on the central "5" key in order to press the key indicated by the target arrow direction (down to "2," left to "4," etc.). Participants initially practiced this under the supervision of the experimenter.

The two parts of the experiment differed only regarding the number of different targets presented within a given block (two vs. four), and were identical in all other respects of stimulus presentation (see **Figure 1B**). Specifically, all five different primes—left, right, up, down, neutral—were presented in each block. However, in a 2-alt block, all targets came from only one spatial dimension (i.e., either all horizontal [left/right], or all vertical [up/down]), whereas in a 4-alt block, targets from both spatial dimensions were mixed. Thus, in effect, each 4-alt block was the combination of one 2-alt horizontal and one 2-alt vertical block.

Responses were expected to be substantially slower in the 4-alt than in the 2-alt task (Hick, 1952; Hyman, 1953). In order to minimize these RT differences, the eight 2-alt blocks (60 trials each) were presented first. Half of the participants started with a series of four 2-alt horizontal blocks followed by a series of four 2-alt vertical blocks (see **Figure 1B**); for the other half, this sequence was reversed. Forty practice trials were given at the beginning of each series. At the end of the first part, participants were encouraged to leave the experimental room for a short rest period. The second part (again starting with a 40-trial practice phase) consisted of eight 4-alt blocks (60 trials each). An overview of all 20 possible prime-target combinations (5 prime × 4 targets) and their distribution across conditions is provided in **Figure 1B**. Within each block, all prime-target combinations were presented randomly and with equal probability, resulting in 20% compatible, 20% neutral, and 20% incompatible trials, plus 40% filler trials[2].

DATA ANALYSES

Repeated measures analyses of variance (ANOVAs) were performed on mean correct RTs, with the between-subject factor of age (young vs. older), and the within-subject factors of task (2-alt vs. 4-alt) and trial type (compatible vs. neutral vs. incompatible). In all analyses, Greenhouse-Geisser correction to the

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[2] The large number of filler trials is an unfortunate side effect of two constraints: (a) primes had to be non-predictive of the upcoming target, because even with subliminal presentation, priming effects are modulated by the primes' predictiveness (see Klapp, 2007). This means that in the 4-alt blocks, a left-pointing prime, for instance, had to be followed with equal probability by a left-, a right-, an up-, and a down-pointing target; and (b) the relevant manipulation in this experiment was the number of possible targets within a block (two vs. four), so consequently, all other factors—particularly the relative frequency of different prime-target combinations—were kept identical between conditions.

degrees of freedom was applied where appropriate, and corrected *p*-values are reported. Because of the large RT difference between age groups (see below), priming effects were calculated not as RT differences, but as RT ratios (benefits = neutral RTs : compatible RTs; costs = incompatible RTs : neutral RTs). ANOVAs were performed on priming effects with the between-subject factor of age group, and the within-subject factors of task and type (benefit vs. cost). Follow-up analyses were conducted in the form of *t*-tests.

Additionally, RTs on filler trials relative to compatible and incompatible RTs were analyzed. Note that in the 2-alt task, primes orthogonally oriented relative to the target have the same general stimulus characteristics as compatible and incompatible primes, but have no explicit response assignment. Therefore, they can be expected to produce RTs intermediate between compatible and incompatible RTs (Wilson et al., 2010). In the 4-alt task, in contrast, these filler primes do have a response assignment, and therefore should affect the visuo-motor system in the same ways as any other incompatible prime. Analyses were conducted using paired *t*-tests, separately for the 2-alt and the 4-alt task and for both age groups. Overall error rates were extremely low (1–3% on average) and thus were not further analyzed.

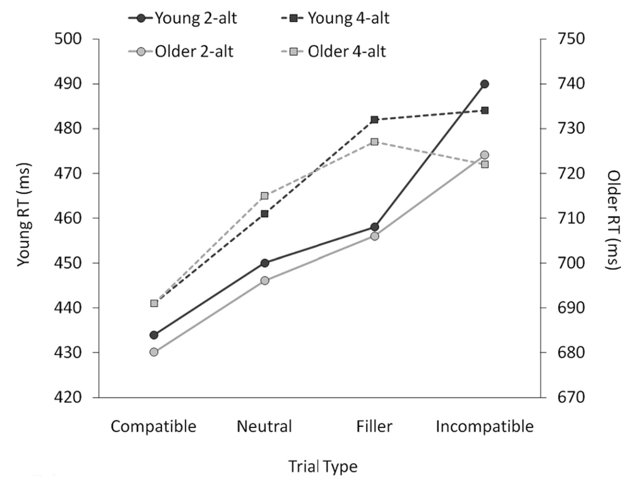

FIGURE 2 | Mean correct response times (RTs) in ms for young and older adults as a function of trial type, plotted separately for the 2-alternative (2-alt) and 4-alternative (4-alt) choice tasks. Note that the two y-axes (left: young adults' mean RTs; right: older adults' mean RTs) use the same scale, but have a 250-ms onset difference.

RESULTS

As can be seen from **Figure 2**, older adults were around 250 ms slower than young adults, [$F_{(1,\ 38)} = 68.18, p < 0.001$]. Although RTs were numerically longer with four than with two response alternatives, this difference was not significant, nor did it interact with age, both *F*s < 1.7, both *p*s > 0.20. There was a highly significant effect of trial type, as RTs increased from compatible to neutral to incompatible trials, [$F_{(1,\ 38)} = 136.67, p < 0.001$]. This priming effect interacted with task (larger priming effects in the 2-alt than in the 4-alt task, [$F_{(1,\ 38)} = 18.76, p < 0.001$]), and with age (young adults showing larger priming effects than older adults, [$F_{(1,\ 38)} = 3.85, p = 0.026$]), but there was no three-way interaction between these factors, $F < 1$.

FILLER-TRIAL ANALYSES

These confirmed our predictions about the impact of a response assignment on priming effects: in the 2-alt task, filler-trial RTs were significantly longer than compatible RTs, and significantly shorter than incompatible RTs, for both young and older adults, all $ts_{(19)} > 3.76$, all $ps < 0.002$. Furthermore, the two RT differences (filler RT minus compatible RT, and incompatible RT minus filler RT) were of approximately the same magnitude in both age groups, both $ts < 1.16$, both $ps > 0.25$. Filler RTs in the 4-alt task were also significantly longer than compatible RTs for both young and older adults, both $ts > 6.90$, both $ps < 0.001$, but in contrast to the 2-alt task, they did not differ significantly from incompatible RTs, both $ts < 1.3$, both $ps > 0.22$.

BEHAVIORAL BENEFITS AND COSTS

These are depicted in **Figure 3**, expressed as ratios of compatible (benefits) and incompatible (costs) to neutral trials (rescaled such that 0 rather than 1 indicates equality of antecedent and consequent). Both types of effects were smaller in older than in young adults, [$F_{(1,\ 38)} = 17.17, p < 0.001$]. However, this age difference was far more pronounced for costs than for benefits, as indicated by a significant Age × Type interaction, [$F_{(1,\ 38)} = 10.38, p < 0.001$]. Follow-up *t*-tests confirmed that whereas benefits did not differ significantly between young and older adults, both $ts < 1.7$, both $ps > 0.11$, costs did, both $ts > 3.66$, both $ps < 0.001$. Furthermore, overall costs were larger than overall benefits, [$F_{(1,\ 38)} = 23.86, p < 0.01$], and priming effects were overall larger in the 2-alt than in the 4-alt task, [$F_{(1,\ 38)} = 5.49, p = 0.024$]. These two effects interacted significantly, as the cost-benefit difference was much larger in the 2-alt than in the 4-alt task, [$F_{(1,\ 38)} = 20.74, p < 0.001$]. Specifically, whereas benefits remained largely unaffected by the number of response alternatives (2-alt vs. 4-alt: $t_{(19)} < 1.6, p > .13$, for both young and older adults), costs were substantially reduced with larger numbers of response alternatives in both young and older adults, both $ts > 3.7$, both $ps < 0.001$[3]. Neither the main effect of task, nor the Type × Task interaction, interacted with age, both $Fs < 1.9$, both $ps > 0.18$.

Next, we conducted multiple regression analyses to examine whether the four priming effects (behavioral benefits and costs in the 2-alt and 4-alt tasks) were independently predicted by any of the background measures (age, visual acuity, vocabulary, and DSST score). The overall regression models were not significant for either 2-alt benefits, adjusted $R^2 = -0.041$; $F < 1$, or 4-alt benefits, adjusted $R^2 = 0.057$; [$F_{(4,\ 33)} = 1.56, p > 0.2$]. However, for 2-alt costs, the overall model was highly significant, adjusted $R^2 = 0.573$; [$F_{(4,\ 33)} = 13.44, p < 0.001$], with DSST alone making an independent contribution to the variance, $t = 4.59, p < 0.001$, such that faster processing speed (higher DSST

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[3] A block-wise analysis of costs showed no gradual decrease in costs over time: costs remained constant throughout the first half of the experiment (2-alt task), then dropped sharply and stayed at the new lower level throughout the second half (4-alt task), thus confirming that the difference in cost magnitude between 2- and 4-alt tasks was not simply due to fatigue.

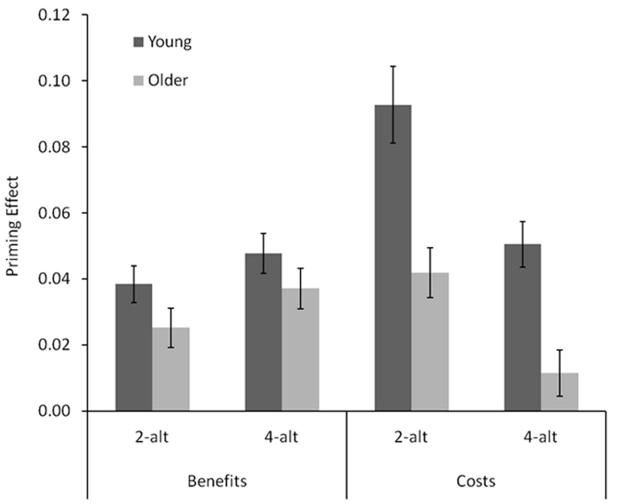

FIGURE 3 | Benefits (neutral RT : compatible RT ratio minus 1) and costs (incompatible RT : neutral RT ratio minus 1) for young and older adults in the 2-alt and 4-alt choice tasks. Error bars represent standard errors.

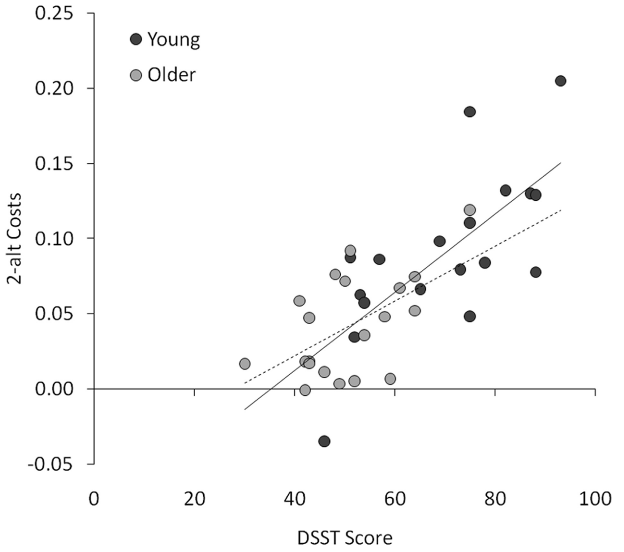

FIGURE 4 | Scatterplot of DSST scores and costs (incompatible RT : neutral RT -1) in the 2-alt task, plotted for young (solid trend line) and older (dashed trend line) participants.

score) was associated with greater reciprocal inhibition (larger behavioral costs; see **Figure 4**). The overall model for 4-alt costs was also significant, adjusted $R^2 = 0.288$; [$F_{(4,\ 33)} = 4.74$, $p < 0.005$], but no measure made a significant independent contribution to the variance (DSST being closest at $t = 1.61$, $p = 0.12$). In other words, with age, visual acuity, and vocabulary already taken into account, DSST significantly predicted behavioral costs in the 2-alt task.

DISCUSSION

Comparing performance in a masked prime task with two and four response alternatives (2-alt vs. 4-alt), the present experiment aimed to confirm that prime-induced motor activation and inhibition processes can be dissociated, and to examine the effect of aging on these separate components. Results replicated the findings of Schlaghecken et al. (2006; Exp. 1): (1) relative to neutral trials, masked primes triggered behavioral benefits on compatible and costs on incompatible trials (PCE); (2) in the 2-alt task, costs were noticeably larger than benefits, possibly because with the stimuli employed in the present experiment, unspecific motor activation triggered by neutral primes (plus signs) is stronger than unspecific activation triggered by arrow primes, leading to a shortening of RTs on neutral-prime trials relative to arrow-prime trials (e.g., Hasbroucq et al., 1999); (3) overall, the PCE was smaller in the 4-alt than in the 2-alt task; and (4) this effect was entirely driven by a reduction of costs with increasing number of response alternatives, whereas the magnitude of benefits was unaffected by this manipulation. The results thus confirm the notion that whereas (compatible-trial) priming benefits measure direct prime activation, (incompatible-trial) priming costs measure the separate and dissociable process of indirect reciprocal competitor inhibition. Importantly, these patterns were observed for both young and older adults, despite the overall differences in response speed (RTs) and competitor inhibition (behavioral costs).

Reciprocal competitor inhibition is assumed to differ from top-down inhibitory control in that it is low-level, automatic, and feed-forward, aimed at fine-tuning the ongoing response execution through the prevention of incorrect response activations (rather than through the suppression of an already activated incorrect response; e.g., Burle et al., 2004; Duque et al., 2010; Tandonnet et al., 2011). Yet as demonstrated by Meynier et al. (2009), this type of inhibition is not hard-wired, but is established in a flexible, task-dependent way. The aim of the present study was to investigate (a) the effect of aging on this type of inhibition, and (b) its possible relationship to speed of processing. Results clearly demonstrated that in the masked prime task, aging selectively affects reciprocal competitor inhibition, not prime-induced motor activation: behavioral costs were much smaller in older than in young adults, whereas behavioral benefits were of similar magnitude. This pattern is in line with the notion that unlike top-down, cue-related activation (e.g., Sterr and Dean, 2008), low-level, prime-induced motor activation remains stable across the adult lifespan (e.g., Schlaghecken and Maylor, 2005), whereas reciprocal inhibitory links in the motor response system deteriorate with advanced age (e.g., Hortobágyi et al., 2006).

It is probably worth noting that in the present experiment, age-related reductions in inhibitory efficiency are reflected in *smaller* interference effects in older compared to young adults, whereas typically, they are reflected in *larger* effects. For instance, in classical response conflict paradigms like the Simon or the Eriksen flanker task, where on incompatible trials an automatically activated incorrect motor response interferes with the execution of the correct response, older participants typically show larger interference effects than young participants, suggesting that their inhibitory control mechanisms are less efficient in overcoming the incorrect response tendency (e.g., van der Lubbe and Verleger, 2002). Those tasks, however, differ from the present one in a crucial aspect: they measure reactive or top-down inhibition of a response that has already been activated. Thus, the less effective the inhibition, the stronger the interference from this inappropriate response. The present task, in contrast, measures the reciprocal inhibition of a response that has not yet been activated. Consequently, the less effective this inhibition, the less this response channel will be deactivated below baseline levels, and the less the execution of this response will be delayed. One might argue, of course, that reactive inhibition of an incorrectly activated response does play a role in the present task as well. However, one needs to keep in mind that because primes were masked, and therefore only of limited accessibility to conscious or high-level control processes, it is likely that frontally mediated top-down inhibition of the incorrect (incompatible) motor activation will have played only a relatively minor role in the current task (e.g., Dehaene et al., 2003; Schlaghecken et al., 2011).

This is not to say that frontal areas are not involved in non-consciously triggered control processes at all. Specifically, the supplementary motor areas (SMA/pre-SMA) have been shown to be directly related to priming effects in the masked prime task (Sumner et al., 2007; van Gaal et al., 2011), and even the anterior cingulate cortex—one of the central structures in high-level cognitive control—has been shown to respond to stimulus irregularities (Ursu et al., 2009) and response errors (Nieuwenhuis et al., 2001) of which participants are not consciously aware. It seems tempting to speculate whether these apparent separate forms of inhibitory control are merely increasingly complex or wide-spread instantiations of the same underlying basic process of reciprocal inhibition. Future research will undoubtedly explore this issue in more detail, specifically with regard to inhibitory dysregulation in psychological and neurological disorders and in normal aging.

The present study provides one step in this direction, as it demonstrated that the strengths of reciprocal inhibitory links might be related to the general speed of information processing. Independent of age, visual acuity, and crystallized intelligence, processing speed (as measured by DSST scores) positively predicted competitor inhibition (as measured by the magnitude of behavioral costs in the 2-alt masked prime task). To the best of our knowledge, this is the first time that direct evidence has been provided that performance in the DSST is associated with low-level inhibitory control. Performance in processing speed tasks has previously been linked to the ability to ignore distracting information (Lustig et al., 2006), an ability strongly associated with prefrontal lobe functions (e.g., Everling et al., 2002). However, the present results—while generally supporting the notion of a relationship between DSST performance and inhibition—suggest that this relationship might be mediated by more basic processes than top-down inhibitory control. One possible interpretation is that more efficient reciprocal inhibition of competing response alternatives allows for generally faster response execution (recall that mean RTs in the priming task were approximately 250 ms shorter in young than in older participants), resulting in the ability to produce more responses within a given amount of time. This interpretation, however, seems somewhat simplistic, and does not fit well with the present data: if faster response execution due to reciprocal inhibition accounts for improved DSST performance, then DSST scores should have been negatively correlated with RTs, particularly on compatible trials, where the "foregrounded" response has to be executed. This was not the case (all $rs < 0.40$, all $ps > 0.08$), suggesting that DSST scores are not merely a function of efficient motor execution. Alternatively, one might assume that the same neural mechanism that instantiates reciprocal inhibition in the motor system produces the attentional focus needed in the DSST and similar processing speed tasks. Again, future research will have to investigate this issue more directly.

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When unconscious rewards boost cognitive task performance inefficiently: the role of consciousness in integrating value and attainability information

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Research has shown that high vs. low value rewards improve cognitive task performance independent of whether they are perceived consciously or unconsciously. However, efficient performance in response to high value rewards also depends on whether or not rewards are attainable. This raises the question of whether unconscious reward processing enables people to take into account such attainability information. Building on a theoretical framework according to which conscious reward processing is required to enable higher level cognitive processing, the present research tested the hypothesis that conscious but not unconscious reward processing enables integration of reward value with attainability information. In two behavioral experiments, participants were exposed to mask high and low value coins serving as rewards on a working memory (WM) task. The likelihood for conscious processing was manipulated by presenting the coins relatively briefly (17 ms) or long and clearly visible (300 ms). Crucially, rewards were expected to be attainable or unattainable. Requirements to integrate reward value with attainability information varied across experiments. Results showed that when integration of value and attainability was required (Experiment 1), long reward presentation led to efficient performance, i.e., selectively improved performance for high value attainable rewards. In contrast, in the short presentation condition, performance was increased for high value rewards even when these were unattainable. This difference between the effects of long and short presentation time disappeared when integration of value and attainability information was not required (Experiment 2). Together these findings suggest that unconsciously processed reward information is not integrated with attainability expectancies, causing inefficient effort investment. These findings are discussed in terms of a unique role of consciousness in efficient allocation of effort to cognitive control processes.

Keywords: rewards, conscious and unconscious processing, attainability, motivation, cognitive control, performance

Motivation is an essential determinant of cognitive control and performance (Watanabe, 2007). Accordingly, a vast body of research has studied how rewards affect cognition and behavior (Wood et al., 1999). Whereas the neuro-cognitive processes underlying the effects of rewards on human cognition and behavior are not yet entirely understood (Chiew and Braver, 2011), it has become clear that the anticipation of rewards can cause people to increase their effort and performance on various cognitive and behavioral tasks (Brehm and Self, 1989; Camerer and Hogarth, 1999; Bonner and Sprinkle, 2002).

Most research on the effects of rewards on the control of cognition and behavior has focused on consciously communicated rewards. In these studies people are fully aware of the specific reward that can be gained through optimal performance on a task. However, research on unconscious processes in the motivation and control of goal-directed behavior challenges the assumption that conscious awareness of rewards is necessary to boost performance of cognitive control or working memory (WM) processes (Nieuwenhuis et al., 2001; Hassin et al., 2009; Bargh et al., 2010; Custers and Aarts, 2010; van Gaal et al., 2010). For instance, studies have shown that high compared to low rewards boost performance on WM tasks even when they are presented unconsciously (for a review see Bijleveld et al., 2012). This intriguing finding offers a new direction to understanding how rewards affect the control of human cognition and behavior, raising the question of whether conscious reward processing plays a unique role in modulating cognitive performance. In the present study, we aim to explore this issue by investigating how people deal with attainable and unattainable monetary rewards when such rewards are consciously or unconsciously processed.

It has long been recognized that presenting valuable rewards does not necessarily improve task performance (e.g., Hull, 1943; Brehm and Self, 1989). An important factor in determining whether a reward will boost performance is whether the reward is perceived as attainable. Studies addressing the expected value analysis of human decision making have found that when attainability information is provided, people no longer base their decisions to invest effort on the reward value alone, but on the combination of value and attainability (von Neumann and Morgenstern, 1947; Atkinson, 1957, 1964; Vroom, 1964; Brehm and Self, 1989; Camerer and Hogarth, 1999; Bonner and Sprinkle, 2002). Performance increases when a reward is both valuable and attainable, but is reduced whenever a reward is of low value or unattainable. This finding is consistent with the general notion that people are conservative in spending their valuable mental resources (Kool et al., 2010; Gendolla et al., 2012). Thus, from the above studies, it appears that people readily integrate the value of a reward with attainability information in order to avoid wasting effort. However, participants in these studies were always aware of the value of a reward at stake and the potential influence of this reward on their performance. In light of work suggesting that reward pursuit can occur outside of awareness (for a review see Custers and Aarts, 2010), we investigated the question of how cognitive performance is affected by the value of an unconsciously perceived reward in a context where the reward is unattainable.

Recently, researchers have developed an experimental paradigm that allows the examination of this question. In this paradigm, participants are presented with coins of high and low value which can be attained as rewards for successful performance on a task. Importantly, on half of the experimental trials the reward is presented unconsciously (i.e., subliminally), whereas the rewards are consciously visible (i.e., supraliminally presented) on the other trials. This procedure enables the direct comparison of the effects of conscious and unconscious reward processing on task performance. Using this paradigm, studies have shown parallel effects of conscious and unconscious reward presentation. For instance, in the first study employing this paradigm (Pessiglione et al., 2007) participants could gain rewards by squeezing a handgrip. Not surprisingly, high vs. low value rewards resulted in harder squeezing. Remarkably, people still squeezed harder for more valuable rewards when these were presented subliminally. Other studies have found enhanced mental effort and performance through consciously and unconsciously-presented high rewards on executive control and WM tasks, such as active maintenance and updating of ordered information (Bijleveld et al., 2009; Capa et al., 2011; Zedelius et al., 2011b; Bustin et al, 2012). However, there have also been studies showing that conscious and unconscious rewards in some task contexts can lead to different effects (e.g., Bijleveld et al., 2010, 2011; Zedelius et al., 2011b).

Recently, a theoretical framework has recently been proposed to account for both identical and divergent effects of conscious and unconscious rewards on performance. This framework distinguishes initial (or unconscious) reward processing from full (or conscious) reward processing (Bijleveld et al., 2012). According to this framework, people initially process rewards in rudimentary brain structures that respond to the value of rewards and boost task performance directly by causing increased recruitment of effort. This process is thought to operate without requiring conscious awareness, which explains why unconsciously perceived rewards can enhance performance. After initial reward processing, when rewards are consciously perceived (e.g., by prolonging presentation time from subliminal to supraliminal) rewards may be processed more fully, involving higher-level cognitive processing. In line with previous research on conscious and unconscious perception (Dehaene et al., 1989), this higher-level cognitive processing is thought to enable more complex cognitive processes and strategic behavioral responses, which could explain why conscious reward processing in some task contexts leads to unique effects.

In experiments, initial (or unconscious) and full (or conscious) reward processing is commonly manipulated by presenting masked reward stimuli (e.g., 1 cent vs. 50 cents coins) either for relatively short (i.e., 17 ms) or relatively long durations (i.e., 300 ms). Subsequent subliminality tests are usually administered to provide evidence that the short presentation of masked reward stimuli renders participants unable to identify the reward value of the stimuli. However, it is questionable whether such tests provide conclusive evidence that short stimulus presentation time prevents conscious perception throughout an experimental task. In fact, there is an ongoing debate about what kinds of subliminality tests are capable of providing sufficient proof for unconscious processing (e.g., see Seth et al., 2008; Sandberg et al., 2010). In the present research, we took a different approach aimed at distinguishing conscious from unconscious reward processing by investigating a situation in which the two types of reward processing are predicted to produce different behavioral effects. Specifically, we test the hypothesis that conscious and unconscious reward value processing differ with regard to taking into account attainability information.

As explained above, when consciously processed rewards vary in attainability, people base their decisions to invest effort on the combination of reward value and attainability. Integration of these two types of information prevents wasting resources on valuable yet unattainable rewards or attainable yet low value rewards (von Neumann and Morgenstern, 1947; Atkinson, 1957, 1964; Vroom, 1964; Brehm and Self, 1989; Camerer and Hogarth, 1999; Bonner and Sprinkle, 2002; Rushworth and Behrens, 2008). Research suggests that the value of a reward and the likelihood that a reward can be attained are initially encoded by distinct subcortical brain networks (Rogers et al., 1999; Dreher et al., 2006; O'Neill and Schultz, 2010), and that the integration of these different signals involves higher cortical processing (Knutson et al., 2005; Tobler et al., 2007; Rushworth and Behrens, 2008; Haber and Knutson, 2009). Therefore, based on the framework outlined above, we predicted that the integration of reward value and attainability requires conscious reward processing. Consequently, when the likelihood of conscious processing is reduced (i.e., by short presentation of rewards), people should fail to integrate reward value and attainability information, resulting in inefficient investment of effort and performance.

The notion that conscious information processing allows for greater integration and more flexible behavioral control is central to several information processing approaches to consciousness (Dehaene and Naccache, 2001; Baars, 2002; Dijksterhuis and Aarts, 2010; Morsella and Bargh, 2010). However, empirical studies have thus far found both support for (e.g., Kunde, 2003; Ansorge et al., 2011) and evidence against (e.g., Lau and Passingham, 2007; Hassin et al., 2009; van Gaal et al., 2010) the hypothesis that conscious information processing plays a unique role in modulating cognitive performance. For instance, studies have shown that subliminally presented stop cues can slow down, but rarely fully inhibit behavioral responses (van Gaal et al., 2008, 2009). Moreover, unconscious stop cues failed to elicit the same globally-distributed and sustained pattern of brain activation observed in response to consciously perceived cues. This work suggests that although unconsciously perceived cues can trigger basic cognitive control processes, conscious perception may enable more efficient and flexible control of behavior (Dehaene and Naccache, 2001).

The present study aims to shed more light on possible advantages of conscious over unconscious reward processing by focusing not only on the initial triggering of cognitive performance by consciously and unconsciously perceived rewards, but on how integration of rewards with attainability information affects performance. Because reward value and attainability information are two distinct aspects of rewards (Brehm and Self, 1989; Liu et al., 2007; Tobler et al., 2007; O'Neill and Schultz, 2010), we expect that full or conscious processing of reward information is necessary to integrate these two types of information and arrive at efficient performance. To test this novel hypothesis, we report behavioral data from two experiments in which we presented participants with high and low-value rewards (coins of 50 or 1 eurocents, respectively) that were instructed to be either attainable or unattainable by successfully performing an active maintenance task. To manipulate the likelihood of conscious vs. unconscious processing, the coins were masked and presented either for relatively long (300 ms) or short (17 ms) durations. We manipulated conscious processing of the reward value rather than attainability information in order to connect our research with previous work on conscious vs. unconscious reward processing (Pessiglione et al., 2007; for an overview see Bijleveld et al., 2012).

Importantly, in order to provide evidence that differences between the effects of long vs. briefly presented rewards are not merely caused by the presentation of attainability information, but are due specifically to differences in the ability to integrate the reward value with attainability information, we manipulated the need for information integration across two experiments. As explained below, Experiment 1 was designed to make integration a requirement for efficient performance, whereas Experiment 2 was designed to eliminate the necessity of integration for efficient performance. Based on the theory that conscious and unconscious reward processing differ in the ability to integrate value and attainability, we expected that conscious and unconscious reward processing would lead to different effects in Experiment 1 but not in Experiment 2. We outline the concrete predictions for the two experiments in more detail below.

Experiment 1 was designed to establish different behavioral effects of quick vs. slowly presented rewards when integrating reward value and attainability was required for efficient responses. This was accomplished by testing performance in response to attainable and unattainable high vs. low value rewards in a full within-subject design. Value and attainability are two distinct sources of performance motivation, and hence performance may be increased by higher reward value, or by the fact that a reward is attainable (e.g., Atkinson, 1957, 1964; Vroom, 1964; Brehm and Self, 1989; Bonner and Sprinkle, 2002). However, when both reward value and attainability vary on a trial-by-trial basis, it is essential to integrate on each trial the two sources of motivation to derive an optimal decision to invest effort (e.g., Anderson, 1971; Brehmer and Joyce, 1988). In this context, we expected that when rewards were presented for a relatively long duration, enabling conscious processing, performance should be enhanced selectively for high value attainable rewards. This result would constitute a conceptual replication of previous work (Atkinson, 1957, 1964; Vroom, 1964; Brehm and Self, 1989; Camerer and Hogarth, 1999; Bonner and Sprinkle, 2002). Examining effects of consciously processed rewards also serves as a control condition to verify that attainability information was clearly and unambiguously processed and that participants were able and motivated to take this information into account.

When rewards are presented for a shorter duration, reducing the likelihood of conscious processing, we predicted a different pattern of results. Without the ability to integrate value and attainability information, participants were expected to invest their effort based either on the high (vs. low) value of a reward, or on the fact that rewards could be gained (vs. not), but not on a combination of both sources of performance motivation. This led to the following predictions: First, the instruction that a reward is attainable vs. unattainable should boost performance. Second, the perception of high vs. low value rewards should likewise boost performance. Most importantly, without the ability to integrate value with attainability information, perception of high value rewards should boost performance, even when it is clear that the reward is unattainable. In summary, we expected that performance would be boosted independently by the fact that a reward can be earned and the presentation of a high value coin. This should result in main effects of reward value and attainability.

Experiment 2 was designed to provide attainability information without requiring trial-by-trial integration with reward value. To do so, we manipulated the attainability of rewards between participants. The idea behind this was that when attainability information constitutes a stable dimension for an individual (cf. Waltz et al., 1999), participants can employ a general response strategy that is valid on every trial without requiring integration of incoming information. More specifically, when rewards are always attainable, participants can respond efficiently based on reward value alone. Likewise, when rewards are always unattainable, the decision to invest effort can be based on this information alone, neglecting the reward value. Hence, in Experiment 2 participants were expected to perform better for high vs. low attainable rewards regardless of whether rewards were presented for long or short duration (e.g., Pessiglione et al., 2007; Zedelius et al., 2011b). Moreover, we expected participants to perform equally well for unattainable rewards, regardless of whether rewards were presented for long or short duration.

EXPERIMENT 1

METHOD

Participants and design

Participants were 41 undergraduate students (28 female). A 2 (presentation duration: long vs. short) × 2 (value: low vs. high) × 2 (attainability: attainable vs. unattainable) within-participants design was employed.

Procedure

Participants performed a verbal active maintenance task in which they were asked to actively maintain word spans of five one-syllable nouns in WM while inhibiting mild distraction during a short delay interval (see Conway et al., 2005; Zedelius et al., 2011b). For an overview of the procedure including pictures of the reward- and masking stimuli, see **Figure 1**. Participants were told that on every trial of the maintenance task, coins were presented that served as rewards for correct responses. Participants were further told that the coins would sometimes be “difficult to perceive” (referring to the short presentation condition). Furthermore, participants learned that the money would not always be attainable, and that they would be paid the amount of rewards earned on attainable reward trials at the end of the experiment.

Each trial started with the message, “Reward can be attained” or “Reward cannot be attained”, presented for 2000 ms. Following a previously developed procedure, a fixation cross was then shown on the screen for 1000 ms, followed by a mask (a scrambled picture of both 1 and 50 cents coins) for 1000 ms, followed by the presentation of a 1 cent or 50 cents coin. The coin was presented for either 300 ms (long presentation condition) or 17 ms (short presentation condition) and followed by a post-mask presented for 600 ms, minus the duration of the coin. Subliminality of the stimuli was tested in a separate detection task with 25 different participants. On each trial, participants saw a coin (1 cent vs. 50 cent), presented in the same way as in the experiment (17 ms in between masks). After each coin, participants indicated the value of the coin. A t-test indicated identification of the coins was no better than chance ($M = 0.51$, $SD = 0.11$), $t(24) = 0.43$, *n.s.* (see Bijleveld et al., 2009 for another subliminality check of this procedure)[1].

After the coin presentation, the target words were presented for 400 ms per word, with an inter-word interval of 200 ms. The presentation of the target words was followed by a delay period during which mildly distracting letter strings were shown for 800 ms each intermitted by intervals of 500 ms. After this delay period, participants were asked to verbally report the target words. Performance was considered correct when all five words were correctly reported. The order in which the words were reported could be arbitrary (see Zedelius et al., 2011a, for the validity of this measure). Finally, accuracy feedback and, for attainable reward trials, the amount obtained was shown.

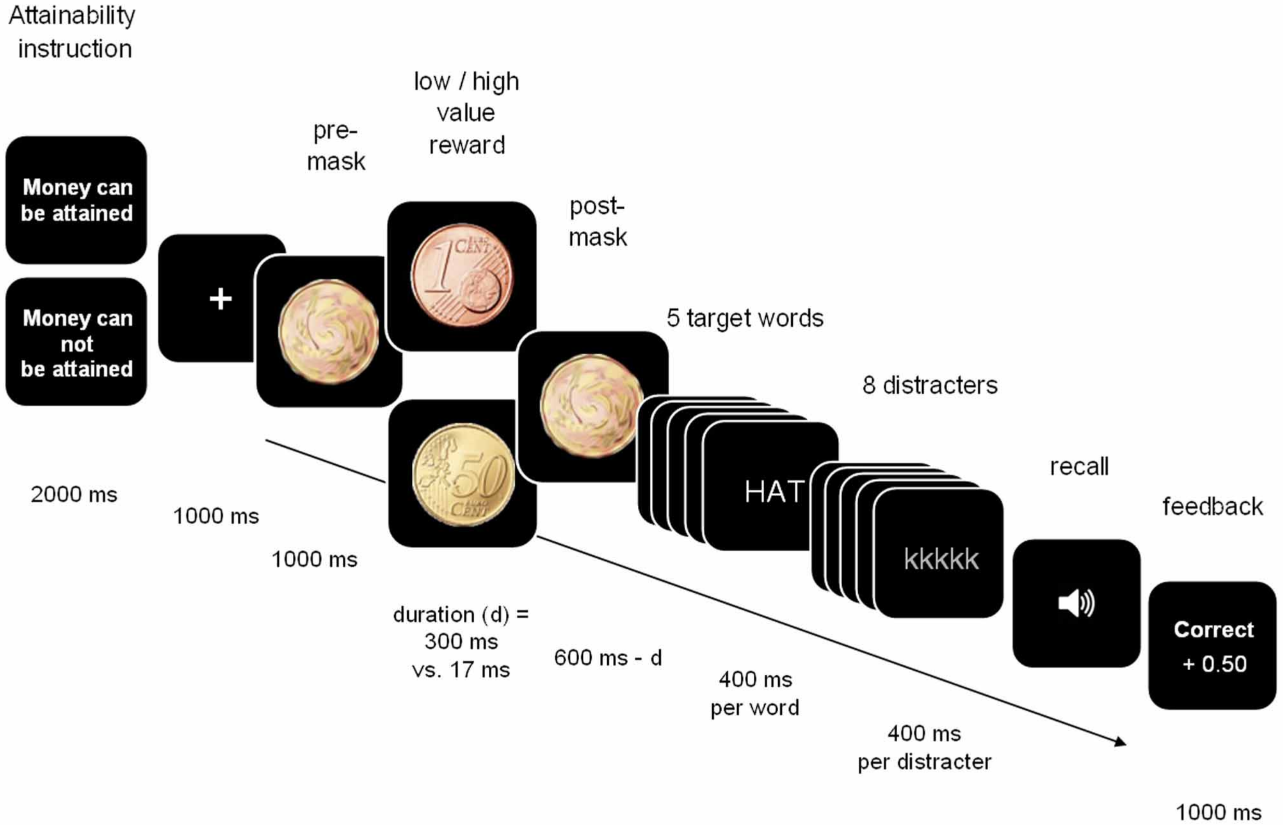

FIGURE 1 | Overview of the procedure of Experiment 1.

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[1] The fact that coin identification was at chance level calls for an objective assessment that the coins were indeed presented. For this purpose, we ran the experiment again on one of the computers used for data collection, and recorded 18 trials of the 17 ms coin presentation using a camera with a slow motion feature (a Sony NX4), enabling recording of the coin presentation at the rate of 240 frames per second. Inspection of the recordings showed that the coin was visible in each recording.

The task consisted of 56 randomly presented trials (seven repetitions per condition). After the experiment, participants were paid the amount of money they had earned throughout the task. The experiment was conducted according to institutional guidelines and approved by the local ethics committee.

RESULTS AND DISCUSSION

To test our hypothesis that the duration of reward presentation affects the integration of reward value and attainability information, the proportion of correct trials[2] was subjected to repeated-measures ANOVA according to the experimental design. The analysis revealed a main effect of attainability, [$F_{(1,\ 40)} = 4.63$, $p = 0.04$, $\eta_p^2 = 0.10$], qualified by the predicted three-way interaction of presentation duration × value × attainability, [$F_{(1,\ 40)} = 6.20$, $p = 0.02$, $\eta_p^2 = 0.13$] (see **Figure 2**). To test the hypothesis that in the long presentation condition effort is selectively increased when rewards are both high and attainable, we performed a specific contrast comparing performance on the long presented high value attainable reward trials with performance on the other trials within the long presentation condition. This contrast was significant, $F_{(1,\ 40)} = 8.07$, $p = 0.007$, $\eta_p^2 = 0.17$, indicating that performance was indeed selectively increased for high value attainable rewards. This result is in line with classic theories of motivation that predict enhanced effort and performance only when rewards are both valuable and attainable (e.g., Hull, 1943; Brehm and Self, 1989).

In the short presentation condition we expected that reward value and attainability information would boost performance independently, resulting in main effects of reward value and attainability. However, contrary to this prediction, we found no main effect of reward value, $F_{(1,\ 40)} = 1.25$, *n.s.*, and no main effect of attainability, $F_{(1,\ 40)} = 2.52$, *n.s.* Instead, we found a marginally significant interaction of reward value and attainability, [$F_{(1,\ 40)} = 3.50$, $p = 0.07$, $\eta_p^2 = 0.06$]. Further inspection of this interaction with simple effects analyses indicated

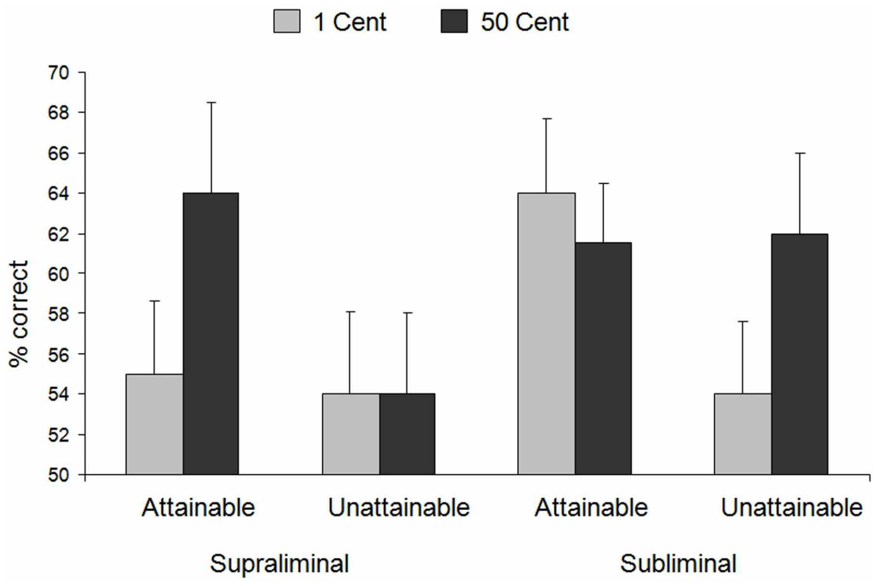

FIGURE 2 | Results of Experiment 1. Mean and standard error of the percentage of correct trials as a function of reward value, presentation duration, and attainability. Error bars = SE.

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[2] Because earning rewards (on attainable reward trials) was contingent on recalling all words correctly, accuracy was operationalized as the correct recall of all five words. Because this demand was clear from the instructions, we reasoned that the total number of words recalled per trial would be a suboptimal performance measure in the present experiment. (For a more detailed discussion of this argument, see Zedelius et al., 2011a). However, for both studies, the pattern of results for the total number of words recalled resembled that of the accuracy data. Specifically, in Experiment 1, analysis of the total number of correctly recalled words yielded a marginally significant main effect of attainability, $F_{(1,\ 40)} = 3.56$, $p = 0.07$, $\eta_p^2 = 0.08$, which was qualified by a marginally significant three-way interaction of attainability × reward value × exposure, $F_{(1,\ 40)} = 3.00$, $p = 0.09$, $\eta_p^2 = 0.07$. When rewards were attainable, performance was higher for high ($M = 4.32$, $SD = 0.59$) compared to low value rewards ($M = 4.08$, $SD = 0.72$) in the long presentation condition, $F_{(1,\ 40)} = 5.18$, $p = 0.03$, $\eta_p^2 = 0.11$, but performance was equally high for high ($M = 4.33$, $SD = 0.52$) and low ($M = 4.31$, $SD = 0.46$) value rewards in the short presentation condition, $F_{(1,\ 40)} = 0.12$, *n.s.* When rewards were unattainable, performance did not differ for high ($M = 4.16$, $SD = 0.69$) and low value rewards ($M = 4.16$, $SD = 0.61$) in the long presentation condition, $F_{(1,\ 40)} < 0.001$, *n.s.* Performance appeared to be somewhat higher for high ($M = 4.19$, $SD = 0.72$) compared to low ($M = 4.12$, $SD = 0.60$) value rewards in the short presentation condition, although this latter increase was not statistically significant ($F_{(1,\ 40)} = 0, 71$, *n.s.*). In Exp. 2, we found a significant interaction of attainability x reward value, $F_{(1,\ 31)} = 5.18$, $p = 0.03$, $\eta_p^2 = 0.14$, indicating performance was not influenced by the reward value in the unattainable reward condition (high reward value: $M = 4.16$, $SD = 0.50$; low reward value: $M = 4.20$, $SD = 0.44$), $F_{(1,\ 31)} = 0.38$, *n.s.*, but performance was increased for high ($M = 4.32$, $SD = 0.40$) vs. low value rewards ($M = 4.13$, $SD = 0.58$) in the attainable reward condition, $F_{(1,\ 31)} = 6.33$, $p = 0.02$, $\eta_p^2 = 0.17$, and this effect did not differ for the long and short presentation conditions, $F_{(1,\ 31)} = 0.21$, *n.s.*

that performance increased in response to high vs. low value rewards when these were unattainable, [$F_{(1,\ 40)} = 4.52, p = 0.04, \eta_p^2 = 0.10$]. Thus, consistent with the prediction outlined in the introduction, high reward value of briefly presented coins boosted performance even when the reward was unattainable (note that the clarity of the attainability information can be inferred from the conscious reward condition). Moreover, and consistent with the prediction that the opportunity to obtain a reward would boost performance in the short presentation condition, we found that performance was increased in response to attainable compared to unattainable low value presented rewards, [$F_{(1,\ 40)} = 6.31, p = 0.02, \eta_p^2 = 0.14$]. However, and contrary to our expectation, we found that performance on attainable reward trials was equally high for both high and low value coins, $F < 1$. The absence of a boosting effect of high value in this latter comparison likely explains why we did not obtain the expected two main effects.

How can we explain the unexpected finding that performance in the briefly presented attainable reward condition was unaffected by the value of the rewards? First, we can rule out that the value of the rewards was not encoded in the short presentation condition. This is attested by the effect of reward value in the briefly presented *unattainable* reward condition. We can also rule out that the absence of an effect of value in the attainable reward condition was merely due to a lack of statistical power. That is, previous research testing the effects of attainable rewards on performance using the same experimental task and procedure (Zedelius et al., 2011b; low distraction condition) indicates that the effect of briefly presented rewards is of small to medium size ($d_z = 0.41$; Cohen, 1988). According to a power analysis using the statistical software G*Power 3.1 (Faul et al., 2009), the chance of detecting an effect of this size with a desired statistical power of minimally 0.80 at an alpha level of 0.05 requires a sample of at least 39 participants, which we exceeded in the present experiment.

Accordingly, we think that there may be a theoretical explanation for why performance in the briefly presented attainable reward condition was unaffected by reward value. As argued above, without the ability to integrate reward value and attainability information, the mere fact that a reward is attainable should cause participants to recruit effort to perform well. This hypothesis was confirmed by the fact that performance was boosted in response to low value attainable rewards within the short presentation condition. The question is whether performance can be increased even further by the presentation of an attainable high value reward. The absence of a main effect of value suggests that this may not be possible. One straightforward explanation for the absence of a value effect in this condition is that the mere opportunity to gain a reward already promoted maximal investment of effort, leaving no room for an additive effect of high reward value on performance. This explanation is consistent with other research showing that factors that independently increase motivation for action (e.g., testosterone and reward cues) do not produce additive effects, probably because motivation is already boosted to its limits by one factor alone, minimizing the contribution of a second source of motivation (see Aarts and van Honk, 2009). This argument implies that we should obtain an effect of value when variation in attainability is not a source of performance enhancement. This issue is addressed in Experiment 2.

Because this experiment is the first examination of conscious and unconscious reward effects under varying attainability conditions within the same task, one question that comes to mind is whether performance in response to attainable and unattainable rewards was influenced by reward attainability on the previous trial. Although we did not predict this, it is an interesting possibility that should be taken into account in light of evidence for performance adjustments instigated by specific trial sequences (e.g., Kunde, 2003; Boy et al., 2010; Ansorge et al., 2011). Therefore, we explored whether attainability sequence (i.e., whether attainability on trial n was the same vs. different from trial *n*–1) affected the results reported above. Specifically, we performed an additional repeated-measures ANOVA with the factors reward value, presentation duration, attainability, and attainability sequence. The results showed no main effect of attainability sequence, and no interaction effects of attainability sequence with any of the above reported factors (all Fs < 1.14). These findings indicate that the differential effects of attainable and unattainable rewards were not affected by the presence or absence of the chance to attain a reward on the previous trial.

Another question that may be raised is whether different effects of long vs. short presentation of attainable and unattainable rewards may be driven by feedback learning. Although participants received accuracy feedback on all trails, feedback about the amount of reward obtained could only be given on attainable reward trials. Could differences in feedback between the attainable and unattainable conditions account for the effects reported above? We do not expect this for a number of reasons: first, we used reward stimuli that were familiar to participants from everyday life so that the reward value likely did not require learning. Second, on attainable reward trials, the coins presented at the beginning of a trial were 100% indicative of the amount of reward to be earned given optimal performance. Thus, and unlike in some other studies (e.g., Knutson et al., 2005; Dreher et al., 2006; Bjork and Hommer, 2007; Tobler et al., 2007), there was no ambiguity about the amount that could be earned on each trial. Moreover, an explanation in terms of added learning on attainable reward trials would be inconsistent with the finding that the briefly presented high vs. low rewards selectively increased performance in the unattainable reward condition, where no feedback was given about the reward value. However, to statistically rule out that learning played a role in driving the above effects, we performed an additional analysis including factors of the experimental design and the additional factor block (i.e., first vs. second half of the trials). The results showed that block did not interact significantly with any of the reported effects, and, most importantly, it did not qualify the above mentioned three way interaction of reward value, presentation duration, and attainability, [$F_{(1,\ 40)} = 1.57, ns$]. Consequently, differences in feedback learning from attainable and unattainable reward trials do not seem to account for different effects of long vs. briefly presented attainable and unattainable rewards.

If our predictions outlined in the introduction are correct and conscious compared to unconscious reward processing enables greater integration of value and attainability information, differences between the effects of conscious and unconscious rewards should vanish when people do not need to integrate this information. To test this hypothesis in Experiment 2, we varied attainability information between, rather than within, participants such that the rewards were either always attainable or always unattainable. When rewards are always attainable, only the value dimension is important to boost performance, and no information integration is required. Therefore, we predicted performance to be enhanced by both long and short presentation of high compared to low value rewards. In contrast, when rewards are always unattainable, and thus never worth the effort, incoming information about the reward value becomes irrelevant. In this case, neither kind of reward should affect performance.

EXPERIMENT 2

METHOD

Participants and design

Participants were 33 undergraduates (24 female). The design was a 2 (presentation duration: long vs. short) × 2 (value: low vs. high) × 2 (attainability: attainable vs. unattainable) mixed design with duration and value as within-participants factors and attainability as between-participants factor.

Procedure

The same WM task was used as in Experiment 1, with the only difference that reward attainability instructions varied between participants. In the attainable reward condition, participants were told that the coins displayed throughout the task were rewards that could be attained for accurate performance. In the unattainable reward condition, participants were told that the coins had functioned as rewards for performance in a previous experiment, but that in this Experiment the rewards were unattainable. In this condition, participants received a flat rate of 5 euros for their participation in the experiment. The experiment was conducted in accordance with institutional guidelines and approved by the local ethics committee.

RESULTS AND DISCUSSION

The proportion of correct trials was subjected to an ANOVA according to the design. There were no main effects of presentation duration, $F_{(1,\ 31)} = 1.15$, $p = 0.29$, reward value, $F_{(1,\ 31)} = 2.16$, $p = 0.15$, or attainability, $F < 1$. However, we did find the predicted interaction between value and attainability, $[F_{(1,\ 31)} = 5.62, p = 0.02, \eta_p^2 = 0.15]$. This interaction was not qualified by a three-way interaction with presentation duration, $F < 1$. Simple effects analyses showed, first that when rewards were attainable, both long and short presentation of high compared to low value rewards increased performance, $[F_{(1,\ 31)} = 6.75, p = 0.01, \eta_p^2 = 0.18]$ (see **Figure 3**). This finding is a direct replication of previous studies (e.g., Pessiglione et al., 2007; Bijleveld et al., 2010; Capa et al., 2011; Zedelius et al., 2011b). This replication is particularly important in light of the unexpected finding from Experiment 1 that performance for briefly presented attainable rewards was unaffected by the reward value. As argued above, in a context of varying opportunity to attain rewards (Experiment 1), the instruction that a reward was attainable caused participants to invest maximal effort in response to briefly presented low value rewards, leaving no room for further improved by high reward value. The present findings from the second experiment show that the performance boost for briefly presented low value attainable rewards does not occur when attainability is a fixed factor within participants.

The results further showed that, when rewards were unattainable, performance for both long and briefly presented rewards was unaffected by the reward value, $F < 1$. This finding confirms our prediction that short presentation of unattainable high value

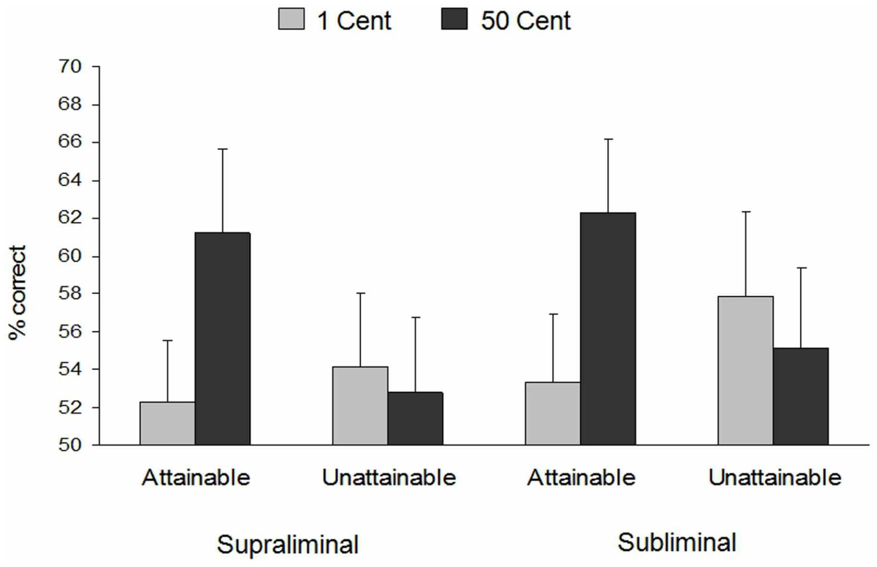

FIGURE 3 | Results of Experiment 2. Mean and standard error of the percentage of correct trials as a function of reward value, presentation duration, and compensation. Error bars = SE.

rewards does not lead to enhanced performance when integration of reward value and attainability information is unnecessary for efficient responding. When it is clear that rewards are never attainable, and hence high value rewards are never worth investing extra effort, people can employ the same general and predefined response strategy throughout the task. That is, they can prepare to ignore the value of rewards even before the rewards are presented. Such a strategy might alter their perception of the rewards such that high value rewards are no longer perceived as valuable or rewarding (Delgado et al., 2008; Staudinger et al., 2009). As such, results of Experiment 2 converge well with work showing that when rewards are irrelevant for behavioral responses, initial reward processing in the subcortical reward system is unaffected by the reward value (Bjork and Hommer, 2007).

In summary, the results from Experiment 2 suggest that both conscious and unconscious reward processing can boost performance efficiently when there is no requirement to integrate value and attainability information. In light of Experiment 1, Experiment 2 provides further evidence that conscious compared to unconscious reward processing promotes the integration of incoming reward value and attainability information.

GENERAL DISCUSSION

The aim of the present study was to test whether conscious compared to unconscious processing of rewards leads to more efficient cognitive task performance based on the successful integration of reward value and attainability information. To examine this question, we first examined the situation in which the need for integration was relatively high by varying value and attainability information on a trial-by-trial basis (Experiment 1). In line with traditional theories of motivation and decision making (e.g., Hull, 1943; von Neumann and Morgenstern, 1947; Atkinson, 1957, 1964; Vroom, 1964; Brehm and Self, 1989), we found that when coins were presented for a relatively long duration, and could thus be consciously perceived, performance increased selectively for valuable and attainable rewards. In contrast, brief presentation of the coins led to rather inefficient effort investment and performance. First, and most stunning, participants worked harder for high compared to low rewards despite their conscious knowledge that the rewards were unattainable. Second, when participants were instructed that rewards were attainable, performance was increased regardless of the reward value. These findings suggest that brief presentation of rewards, which reduces the likelihood of conscious processing, causes failure to integrate reward value and attainability information. Moreover, our data suggest that in the absence of integration, high reward value and information that a reward is attainable do not improve performance in an additive way. Instead, people invest maximal effort in response to either source of motivation.

The fact that performance was more efficient when reward information was presented for a relatively long duration speaks to the hypothesis that conscious awareness enables processes that lead to more strategic behavior. This finding converges well with the framework outlined in the introduction, according to which initial or unconscious reward processing can directly facilitate task performance, but full or conscious reward processing is needed to modulate performance strategically (Bijleveld et al., 2012). Support for the direct facilitation of performance through rewards comes from neuroscience research showing that the value of rewards is first encoded in a subcortical reward network, including most prominently the ventral striatum (VS) (Phillips et al., 2007; Salamone et al., 2009). The VS is also responsible for translating the reward value into effort by projecting to frontal cortical areas, such as the dorsolateral prefrontal cortex, which modulate executive control processes (Aston-Jones and Cohen, 2005; Liljeholm and O'Doherty, 2012; Schmidt et al., 2012). This may explain why unconsciously perceived rewards can facilitate effortful cognitive performance. However, according to the framework (Bijleveld et al., 2012), conscious awareness of rewards allows for more complex, higher-level cognitive processing (see also Dehaene et al., 1989). Such higher level processing likely includes activation of the medial and orbital prefrontal cortex, regions that are involved in evaluating the likelihood that a reward can be attained (Rogers et al., 1999; Knutson et al., 2005; O'Neill and Schultz, 2010). This may explain why consciously processed rewards lead to more efficient effort investment based on the combination of reward value and attainability information.

Further evidence for the crucial role of consciousness in integrating value and attainability information stems from Experiment 2, where we show that long and short presentation of rewards lead to parallel effects on performance when integration of value and attainability was irrelevant. That is, irrespective of presentation duration of the reward information, participants performed better for relatively high attainable rewards, but performance was similar for high and low rewards when these were unattainable. An interesting question raised by this latter finding is whether the coins were still perceived as rewarding when they are always unattainable. Although money is generally desirable (Lea and Webley, 2006), it is possible that the perception of money as a performance reward depends on the potential of attaining it (cf. Biner and Hannon, 1988; Richter and Gendolla, 2006). Further research is therefore needed to determine whether cognitive task performance is boosted by unconscious reward cues as a function of the actual or perceived rewarding property of the cues.

It is important to note that a few recent studies have shown that conscious and unconscious rewards can sometimes have different effects on cognitive control task performance. For instance, it has been shown that conscious, but not unconscious high rewards impair performance when they are presented during the execution of an active maintenance task, probably due to distraction (Zedelius et al., 2011b). Furthermore, while unconsciously presented monetary rewards were shown to reduce the attentional blink effect (assessed by the rapid serial visual presentation task; Raymond et al., 1992), conscious rewards augmented the attentional blink effect resulting from the (normatively learned) tendency to concentrate too much on task stimuli when one knows that rewards are relatively high (Bijleveld et al., 2011). These previous studies point to an advantage of unconscious reward processing in boosting cognitive control performance. The present study contributes to this research by demonstrating that the advantageous or disadvantageous effects of conscious vs.

unconscious rewards depend on the ability to combine relevant information to arrive at efficient cognitive task performance.

The results of the present study have important implications for current debates about the role of consciousness in motivation and decision making (Dijksterhuis and Aarts, 2010; Baumeister et al., 2011). That is, even though information integration is sometimes proposed to be dependent on conscious processing (e.g., Dehaene and Naccache, 2001; Baars, 2002; Dijksterhuis and Aarts, 2010; Morsella and Bargh, 2010; however, see Mudrik et al., 2011), conscious and unconscious processing are rarely compared directly to test differences in integration. Employing a paradigm where conscious and unconscious reward processing can directly be compared, the present study suggests that conscious awareness plays a crucial role in the integration of reward value and attainability information to arrive at an optimal decision about whether it is worthwhile to invest effort. This ability to integrate different types of reward related information may not be constrained to value and attainability information. Even when valuable rewards are attainable, people may judge them not worth the effort, for instance because they are very hard to get or because they are attainable only after a considerable delay (e.g., Kivetz, 2003; Raynolds, 2006). Such judgments imply the combination of reward value with information about effort and time requirements (Ballard and Knutson, 2009). Although the exact mechanisms behind these judgments go beyond the current research, our findings suggest that they may benefit from conscious awareness of rewards.

DIRECTIONS FOR FUTURE RESEARCH

The present findings raise interesting questions for future research. First, given that (attainable and unattainable) unconsciously perceived rewards can motivate people to work, this leads to the question of how people might experience this motivation. Although the framework outlined above makes a qualitative distinction between conscious and unconscious reward processing, this framework does not imply that rewards perceived outside of conscious awareness can never gain access to consciousness, or affect conscious experience in any way. For instance, when people become motivated by unconscious rewards, they may become aware of this motivation, either indirectly, by observing their own behavior, or more directly, by noticing potential changes in their mood or arousal which may be related to their motivated behavior (e.g., Carver and Scheier, 1990; Knutson et al., 2005; Chartrand et al., 2010). Although this topic goes beyond the scope of the current investigation, it remains an interesting direction for future research. Within the present research, however, there is no evidence that potential downstream effects of unconscious rewards on conscious experience could help the strategic control of efficient effortful performance.

Another interesting topic for future research is how conscious expectations with regard to the value of unconsciously processed rewards affect performance and motivation. For instance, would a person work harder for an unconsciously perceived low value attainable reward when he or she consciously expects it to be of high, rather than low value? In the light of the present studies, we can only speculate about this issue. In the present study, when attainability varied throughout the task, participants based their decisions to invest effort either on high value of a reward, or the fact that the reward was attainable. This suggests that people are most strongly influenced by information that triggers motivational behavior. Information that should reduce motivated behavior (i.e., the fact that a high value reward was not attainable, or that an attainable reward was of low value) appeared to have less impact. Therefore, we would predict that conscious expectancies related to reward value could overrule the effects of unconsciously perceived rewards when people expect a high value reward, but unconsciously perceived high value should drive behavior when people expect to work for a low value reward. It would be interesting to test these predictions in future work, for instance by manipulating the (perceived) ratio of high to low value rewards.

CONCLUSION

The present study extended recent research on conscious and unconscious reward pursuit by addressing the issue of how people deal with unattainable rewards. The findings from two experiments with different experimental designs suggest that conscious perception of rewards enables people to integrate the value of monetary rewards with fluctuating attainability information. Thus, while consciousness of rewards is certainly not necessary to boost cognitive task performance, it appears to be crucial to arrive at efficient effort investment when confronted with attainable and unattainable rewards.

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Automatic motor activation in the executive control of action

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Although executive control and automatic behavior have often been considered separate and distinct processes, there is strong emerging and convergent evidence that they may in fact be intricately interlinked. In this review, we draw together evidence showing that visual stimuli cause automatic and unconscious motor activation, and how this in turn has implications for executive control. We discuss object affordances, alien limb syndrome, the visual grasp reflex, subliminal priming, and subliminal triggering of attentional orienting. Consideration of these findings suggests automatic motor activation might form an intrinsic part of all behavior, rather than being categorically different from voluntary actions.

Keywords: action, cognitive control, response inhibition, unconscious, volition

It is widely believed that human cognition and behavior is governed by both voluntary and automatic processes. Voluntary "executive control" mechanisms are assumed to direct behavior in goal-directed ways through use of explicit knowledge and expectations. On the other hand, accumulating research has revealed that perceptual processing of visual stimuli can automatically and unconsciously modulate motor responses (see e.g., Eimer and Schlaghecken, 2003; Sumner, 2007). Traditionally, the processes underpinning automatic and unconscious triggering of actions have been considered separate from the processes underpinning voluntary action planning and control. Embedded in this concept of separate functional pathways is the idea that automatic processes are unconscious, fast, and rigid whereas voluntary action planning and control were considered to be conscious, and flexible (see e.g., Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977, 1984). However, several lines of evidence, briefly reviewed previously by Sumner and Husain (2008), challenge this traditional distinction.

In this review we consider recent empirical findings and discuss how they provide evidence that voluntary and automatic control of action might not in fact be so distinct. We suggest that many "automatic" mechanisms can in fact be surprisingly flexible, quite unlike the traditional, inflexible view of these processes. We begin by reviewing evidence that even simple, flashed visual stimuli can automatically modulate on-going motor responses. Then we discuss how automatically primed responses might affect interactions with real objects in the world around us, focusing on the subject of object affordance. Finally we turn to the issue of how such primed activity might be controlled, and to what extent such control could be automatic. Throughout the review, we draw on evidence from three converging approaches: using subliminal priming paradigms to show that unconscious motor activation can also be reversed unconsciously; using traditional "conscious inhibition" paradigms to show that such inhibition can also be triggered automatically; using the two types of paradigm together to see if they interact. The demonstration of flexible control over automatic processes suggests an intricate link between these historically distinct processes.

EVIDENCE FOR AUTOMATIC ACTIVATION OF MOTOR RESPONSES

Perceptual processing of a visual stimulus can result in motor responses even when the observer does not intend to act. One of the most well-studied of these phenomena is the "visual grasp reflex", where an observer makes a fast, reflexive eye movement (saccade) toward a suddenly appearing—and irrelevant—visual stimulus, despite their intention to look elsewhere (e.g., Theeuwes et al., 1998; Irwin et al., 2000). Even when irrelevant distractors do not fully succeed in capturing gaze they may nevertheless have a remarkable influence on on-going motor activity. For example, saccades can curve whilst in flight toward an irrelevant distractor on the way to correctly landing on the target (e.g., McPeek and Keller, 2001; Godijn and Theeuwes, 2002; McPeek et al., 2000, 2003). But as response latencies increase, saccades are more likely to curve *away* from a distractor (e.g., Walker et al., 2006), revealing an inhibitory mechanism acting to suppress unwanted motor activity toward the irrelevant stimulus (e.g., Sheliga et al., 1995).

Saccades toward targets can also be slowed when an irrelevant distractor is presented simultaneously—or nearly simultaneously—with the target (the saccade distractor effect; e.g., Walker et al., 1995, 2000). Furthermore, transient changes to the scene during saccade planning in simple tasks, reading, or visual search produce a characteristic "dip" in the frequency of saccades made around 90–100 ms after the change (saccadic inhibition effect; e.g., Reingold and Stampe, 1999, 2000, 2002, 2003; Buonocore and McIntosh, 2008; Edelman and Xu, 2009; Bompas and Sumner, 2011). These dips provide highly robust evidence for rapid modulation of on-going motor commands by visual information. Manual reaching responses too are affected by irrelevant non-target stimuli. Like saccades, reaches can be slowed (e.g., Tipper et al., 1997), curve toward (e.g., Tipper et al., 1997) or away from (e.g., Howard and Tipper, 1997) non-target stimuli in flight. These findings suggest that both manual and oculomotor responses can be automatically modulated by irrelevant visual inputs.

Although not often considered in this context, such effects of irrelevant stimuli might in fact be related to a long-established view that simply visually processing an object can automatically evoke action plans appropriate for interacting with it. Gibson (1979) described "affordances" as properties of the environment that automatically prime the observer to act in such a way. According to this view, seeing a coffee cup with its handle to the right *affords*—or facilitates—a reaching movement with the right hand to grasp the cup. Recently there has been renewed interest in affordances, and their effects have been examined using functional imaging as well as behavioral methods. For example, motor regions of the brain—such as those within the dorsal medial frontal cortex—are activated when observers merely look at a graspable object (e.g., Grèzes and Decety, 2002), even when they do not intend to act. In other tasks that require arbitrary responses to pictures of graspable objects (such as squeezing a trigger to indicate whether the object is man-made), the response is facilitated when it is congruent with the action afforded by the object (e.g., Tucker and Ellis, 1998; see **Figures 1A** and **B** for examples of typical affordance stimuli and their effects on response times). Findings such as these suggest that the brain has learnt to associate objects with actions appropriate to "capture" them, and these actions can be (partially) activated by visual processing of the object.

However, there has been some debate about whether object affordance effects genuinely arise from visual objects automatically eliciting motor plans. Anderson et al. (2002) observed that the most visually salient part of the objects used in many affordance studies were also often the graspable part of the object. They demonstrated that response times were faster whenever the side of the response corresponded with whichever side of the object was most visually salient, even when the object was not graspable (e.g., left hand responses to a picture of an analog clock showing a time of quarter to nine). Therefore, affordance-like behavioral effects do not necessarily arise from possibilities for action *per se*, but instead can stem from congruence between the required response and this shift of attention.

But this is not to say all affordance effects are perceptual. Object orientation was irrelevant in most other affordance experiments (e.g., Tucker and Ellis, 1998), but by contrast it was the response-defining property of the object in Anderson and colleagues' task. They also used line-drawings of common objects which may have evoked qualitatively different responses than those evoked by the photographs or images of 3D models used elsewhere (e.g., Tucker and Ellis, 1998; Phillips and Ward, 2002; McBride et al., 2012). Furthermore, perceptually lateralized stimuli that do not afford actions do not necessarily produce affordance effects (e.g., Buccino et al., 2009). Finally, object affordance effects have recently been shown with stimuli and responses that are not lateralized, and instead rely on compatibility between object size and response (pinch or power grasp) to produce affordance effects (e.g., Ellis and Tucker, 2000; Tucker and Ellis, 2001; Derbyshire et al., 2006; Ellis et al., 2007). These considerations suggest that there are good reasons to believe perceptual processing of graspable objects can automatically evoke motor responses associated with them.

ALIEN HAND SYNDROME AND UTILIZATION BEHAVIOR

Some of the most striking evidence that visual objects can indeed automatically generate responses comes from studies of some unusual neurological cases. Patients with alien hand syndrome spontaneously and involuntarily grasp objects—even other people—in their environment as if magnetically drawn to them (for a review see Scepkowski and Cronin-Golumb, 2003). These individuals are aware of their hand making these movements, but report that they are not controlling them, and instead feel the movements are being controlled by an external agent. In a related syndrome, patients who display *utilization behavior* automatically grasp and use objects placed within their reach, even when the objects are not needed. For example, they may grasp and begin to peel an apple placed within their reach, even though they are not hungry, do not want to eat the apple, and know that it doesn't belong to them (e.g., Boccardi et al., 2002).

Alien limb and utilization behavior are rare neurological syndromes, and so case reports and experimental studies on patients with them have been correspondingly few. Some of the most detailed investigation comes from Riddoch and her colleagues (Riddoch et al., 1998; Humphreys and Riddoch, 2000). They showed that patients with an alien right hand can correctly pick up a cup with the left hand as long as the cup's handle is also on the left. However, when the handle is on the right the patients are more likely to grasp the cup with the right hand, despite instructions to the contrary. These "interference" errors were reduced when the task was to point to the object, rather than grasp, and also when the objects were inverted. Therefore, it seems that these patients responded according to well-learnt affordance-action associations rather than according to the instructions they were given. The action afforded by the object was disrupted when the object was inverted, or when the action required was not the one usually made to the object (pointing instead of grasping), so fewer interference errors were reported under these conditions.

Alien limb and utilization syndromes are most often associated with focal lesions to the medial frontal lobes (particularly the supplementary motor area; SMA e.g., Lhermitte, 1983; Boccardi et al., 2002), but have also been associated with damage to the corpus callosum (e.g., Biran and Chatterjee, 2004), as well as patients with parietal lesions following posterior cerebral artery stroke (e.g., Coulthard et al., 2007; Bartolo et al., 2011). Increasingly, they are recognized in patients with corticobasal degeneration (CBD), a slowly progressive neurodegenerative condition which affects cortical regions as well as the basal ganglia (e.g., Murray et al., 2007; Tiwari and Amar, 2008).

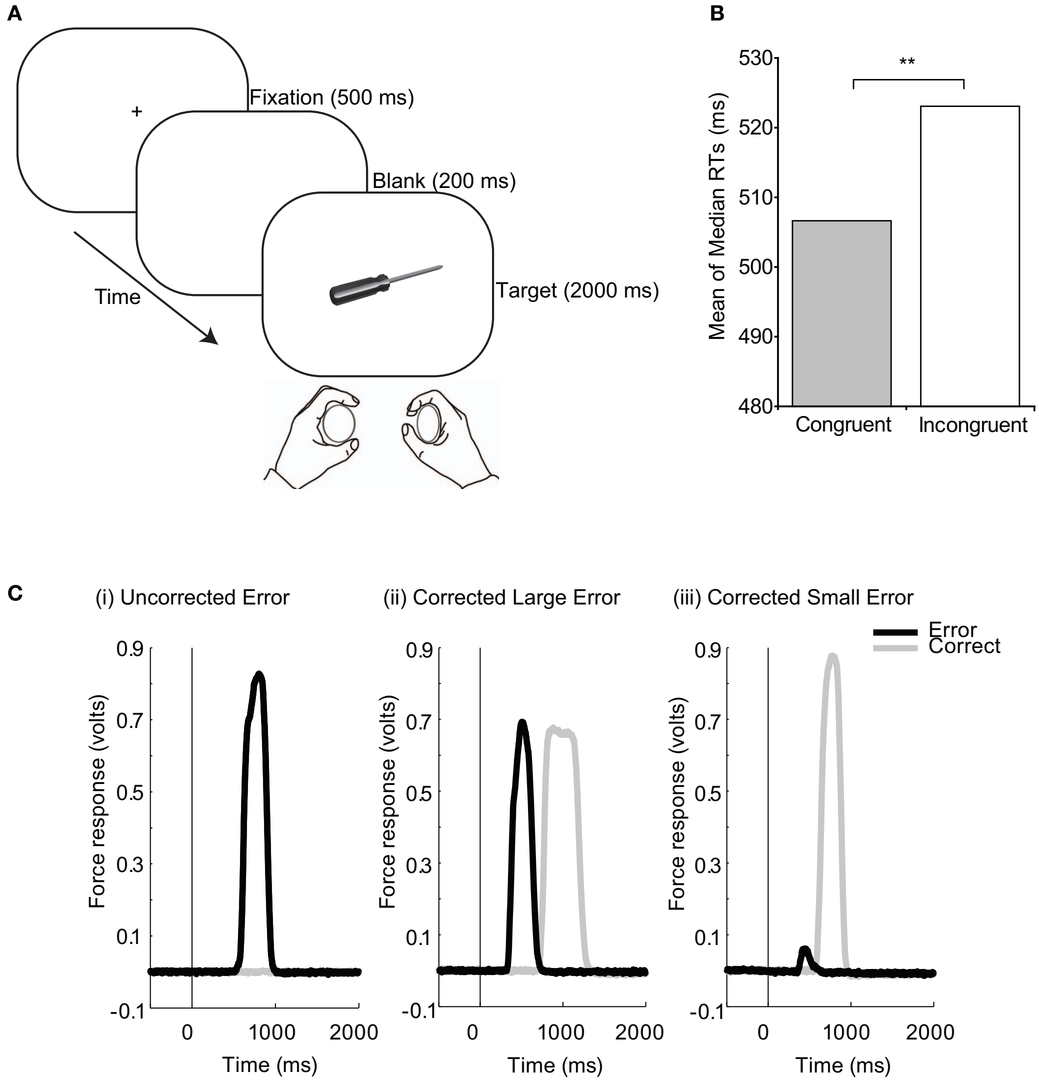

FIGURE 1 | McBride et al. (2012) studied automatic priming of motor responses by visual objects in an object affordance task. Here, participants made speeded squeeze responses with either their left or right hand according to whether the object presented on each trial belonged in a kitchen or a toolbox (see **A** for task details). The objects could also afford a grasping action with either the left or right hand. Although object affordance was irrelevant to the task, it still modulated responses so that they were faster when the object afforded a congruent response than an incongruent one **(B)**. Furthermore, partial squeeze responses (see **C(ii)** and **C(iii)** for examples of the responses recorded on individual trials) were made significantly more often on incongruent than on congruent trials—indicating that the afforded response had been activated and at least partially executed on incongruent trials. These figures are adapted with permission from Taylor and Francis and were originally published in McBride et al. (2012), *Q. J. Exp. Psychol. 65,* 13–24, www.tandfonline.com.

In a recent functional imaging study, Schaefer et al. (2010) examined the neural correlates of unwanted movements in a patient with alien limb syndrome with CBD. They reported that voluntary and alien movements activated similar brain regions, including motor and parietal cortices. However, the right inferior frontal gyrus (rIFG), which has been associated with inhibitory control of motor responses (e.g., Swann et al., 2009, 2012; Hampshire et al., 2010; Verbruggen et al., 2010; see also Aron, 2007), was activated only during alien movements. Such activation may reflect unsuccessful attempts to inhibit alien movements. Taken together, these studies highlight the impact of automatically afforded actions, and suggest that alien limb patients might find them particularly difficult to inhibit.

EVIDENCE FOR AUTOMATIC MOTOR ACTIVATION FROM "PARTIAL" ERRORS

Another line of evidence that potentially reveals the automatic effects of visual stimuli on actions comes from investigation of erroneous responses. Typically, most evidence for automatic motor priming by visual objects has been gleaned indirectly by measuring the eventual outcome of this process on reaction times, usually for manual button presses. Such responses are an all-or-nothing, binary measure: either the response made is of sufficient magnitude to trigger a button press, or it isn't. However, it is possible that small amounts of force applied (erroneously) to a button might be insufficient to trigger a measurable response and thereby escape detection.

With this in mind, there has recently been revived interest in employing continuous and sensitive measures of motor response to more directly investigate processes of automatic motor activation on a trial-by-trial basis. McBride et al. (2012) employed such a measure to investigate object affordances. They asked participants to classify object stimuli by squeezing one of two devices placed in their left and right hands (see **Figure 1A**) while measuring the force applied by either hand. Consistent with object affordance effects, responses were faster on trials where the object afforded an action with the same hand that was required to make the response (congruent trials), compared to the opposite hand (incongruent trials). But continuous, simultaneous force recordings also revealed that participants made small erroneous responses when there was conflict between the response afforded by the object and the response required by the task, i.e., when the stimulus afforded a response that was incongruent to the response required by the task. Such errors were later corrected (**Figure 1C**). These partial erroneous responses provide compelling evidence that viewing an object activates motor plans appropriate for interacting with that object, sometimes going far enough to produce a partial response.

Electromyography (EMG) has also been used to demonstrate "sub-threshold" erroneous responses on incompatible compared to compatible trials in a variety of paradigms including Eriksen flanker (e.g., Coles et al., 1985; Eriksen et al., 1985), and Simon (e.g., Burle et al., 2002) tasks. For example, continuous measurement of EMG from both arms of participants performing a flanker task has demonstrated that correct button-press responses on incompatible trials are frequently accompanied by some muscle activity in the opposite hand, i.e., for the response associated with the irrelevant flanker stimuli (Eriksen et al., 1985). Thus, response-related muscle activity measured by EMG could be measured in the absence of a "full" button-press response.

Such increased erroneous response activity on incongruent trials provides strong evidence that an irrelevant stimulus—or part of a stimulus—can automatically activate responses associated with it. These responses are not merely partially activated somewhere in the brain; the response can be measured in the muscles or in small hand movements with force transducers. These "partial" responses are not captured by current the models of decision-making, which instead assume that actions are either executed wholly once the threshold for accumulated evidence is reached, or not executed at all (see Smith and Ratcliff, 2004 for a review of commonly used models and their characteristics). These models assume that evidence in favor of particular action possibilities is accumulated until a certain threshold of evidence is reached. Models differ in how evidence accumulates. Some (e.g., random-walk) assume that evidence is accumulated as a single total so that evidence in favor of one response is necessarily evidence counter to alternative responses (e.g., Link and Heath, 1975), whereas others (e.g. accumulator models e.g., Usher and McClelland, 2001) assume that evidence in favor of competing responses is accumulated separately, often with mutual inhibition between the separate accumulators.

Importantly, all these decision models share the assumption that once the accumulated evidence reaches a "threshold," the response is executed. This all-or-nothing property of decision models does not allow any gradation of the response. Either the evidence accumulating for a particular response reaches the decision threshold and the response is made, or it does not reach threshold and no response is made. We anticipate that investigations of partial responses evoked by automatic activation of motor responses will provide interesting constraints for future work in decision-making.

INVISIBLE INFLUENCES

Thus far, in the evidence we have reviewed, the automatic nature of motor priming has been inferred from interference effects: if the participant or patient is engaged in a particular task and stimuli interfere with that task, we infer that responses to the task-irrelevant stimulus (or part of a stimulus) were not volitional. Another way to study automatic influences is to investigate the effects that *invisible* stimuli have on motor behavior. If an observer is unaware of a stimulus, then traditionally it is concluded that any response made to it cannot have been evoked voluntarily and must, therefore, have been made automatically.

One way to present a stimulus subliminally is to use the *backwards masking* technique (e.g., Ögmen and Breitmeyer, 2006). Using this technique, participants are usually required to make a manual button press as quickly as possible to a target stimulus (often a left or right pointing arrow). This target is preceded by a "prime" stimulus for a very short duration (say, 20 ms) which is followed by an overlapping (or surrounding in the case of metacontrast masking) stimulus—or "mask." This technique renders the prime stimulus imperceptible to the observer. Even when the participants cannot discriminate the identity of the prime under forced choice, responses are generally faster and more accurate when the prime stimulus was associated with the same response as the target stimulus (compatible trial) compared to when the prime was associated with the opposite response (incompatible trial; e.g., Leuthold and Kopp, 1998). Thus, manual responses can be partially activated automatically by visual stimuli even when they cannot be consciously discriminated.

Subliminal stimuli can also prime a shift of attention (e.g., McCormick, 1997; Ivanoff and Klein, 2003; for a review see Mulckhuyse and Theeuwes, 2010) so that observers respond more quickly and accurately to stimuli presented at the cued location relative to an un-cued location. For instance, McCormick (1997) manipulated the luminance of cues so that some were visible and others were not. The cues were mostly *invalid* so the target was most likely to appear at the opposite location to the cue. When participants perceived the cue they were faster to respond to a target presented at the location opposite the cue, suggesting that they had *volitionally* moved their attention to the most appropriate (i.e., statistically predicted) location. However, when participants were not aware of the cue they were faster to respond to targets at the cued, relative to un-cued, location. This provides evidence that the invisible cue produced an *automatic* and *involuntary* shift of attention to the cued location.

Cues do not have to be based on low-level differences in visual salience in order to produce reliable effects. Socially relevant eye-gaze can also direct attention exogenously. Responses are faster to target stimuli that have been preceded by a non-predictive face (or schematic drawing of a face) with the eyes gazing in the direction of the target (e.g., Friesen and Kingstone, 1998, 2003; Driver et al., 1999; but see Tipples, 2002). These so-called "gaze cueing effects" have been shown following cues that have been backwards-masked to render them invisible to the participant (Sato et al., 2007). In summary, shifts of attention and motor responses can be automatically and unconsciously triggered by visual stimuli. Effects of non-perceived stimuli such as these have provided key evidence that visual stimuli can automatically prime the observer to act.

INHIBITION OF PRIMED ACTIONS

In the above section, we have reviewed evidence from parallel domains that visual stimuli can automatically generate actions. These automatically generated actions can interfere with the intended or task-relevant response, and can be triggered by stimuli that are not consciously perceived, potentially facilitating responses to them. But an important question that arises is how such automatically primed responses might be controlled to allow flexible, goal-directed, behavior. For it would not be useful to respond to every object that we see. Thus, it is necessary to consider how brain systems inhibit or override responses that have been triggered automatically by the environment and are not relevant to our current goals.

"Cognitive control" over simultaneously activated competing motor plans has been extensively studied using "conflict" tasks such as such as the Eriksen flanker task described above (see Eriksen and Eriksen, 1974), the Stroop color-word naming task (e.g., Stroop, 1935) and the Simon task (for a review see Lu and Proctor, 1995). In these tasks, multiple responses can be simultaneously activated and in conflict: one response according to the task instruction and one evoked automatically by the irrelevant stimulus (or irrelevant property of the target stimulus). Typical theoretical frameworks for the congruency effects shown in conflict tasks suggest that stimuli are simultaneously processed by two routes which converge at the level of response programming (e.g., dual route model by Kornblum et al., 1990; activation suppression model by Ridderinkhof, 2002; see **Figure 2A**).

Processing by the fast, *direct processing route* is automatic, and occurs irrespective of task instructions. For example, the spatial location of a target stimulus in a Simon task would be processed quickly and automatically via the direct processing route. At the same time, processing of the task-relevant target attribute (e.g., target color in a Simon task) proceeds via a slower *indirect processing route*. On congruent trials, the same response is activated by both the direct and the indirect processing routes, producing fast, correct responses. On incongruent trials, however, the direct processing route and the indirect processing route activate different responses which results in increased error rates, and slower response times as the conflict between competing responses is resolved.

Importantly, models of information processing in conflict tasks often include an active inhibition mechanism which acts to selectively suppress inappropriate response activation resulting from the direct processing route. Evidence for such control over automatically activated responses can be gleaned by studying the temporal dynamics of interference effects—for example, by plotting the accuracy of responses as a function of response speed as a *Conditional Accuracy Function* (CAF, see van den Wildenberg et al., 2010 for a review; see **Figure 2B**).

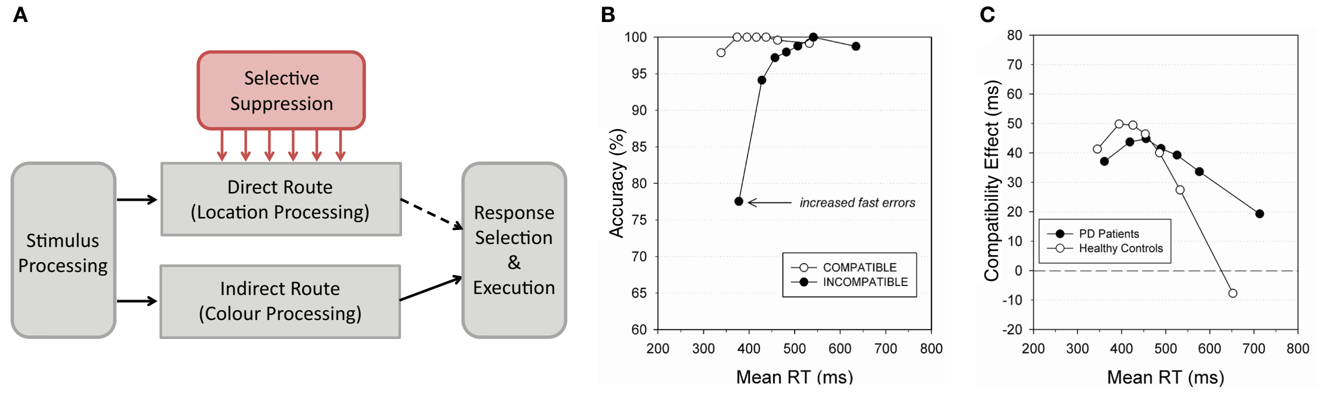

FIGURE 2 | (A) Information processing during a Simon task as modelled by the Activation-Suppression model [e.g., Ridderinkhof (2002)]. The relevant stimulus dimension (color in the Simon task) is processed via the slow, indirect, processing route. Simultaneously, irrelevant stimulus location is processed via the fast, direct, processing route. Activation of the location-based response activation is inhibited by selective suppression (shown here in red), which facilitates execution of the correct, color-based, action. The selective suppression takes time to develop, which results in a relatively high proportion of fast erroneous (location-based) responses on incongruent trials, with near-perfect response accuracy when responses are slower as the inappropriate responses have been suppressed. These effects seen by plotting response accuracy as a function of response time in a Conditional Accuracy Function (CAF) as shown in **(B)**. Furthermore, the interference on incongruent trials would be expected to reduce as unwanted responses are suppressed as RTs increase. This effect can be seen in the negative slope of a delta plot, as shown in **(C)**. Delta plots can reveal individual and group differences in motor activation and suppression that cannot be seen in average measures of RT.
Panels **(B)** and **(C)** were originally published in van den Wildenberg et al. (2010). *Front. Hum. Neurosci.* 4:222. doi: 10.3389/fnhum.2010.00222. Panel **(B)** was modified after Wylie et al. (2009), with permission from Elsevier. Panel **(C)** was modified after Wylie et al. (2010).

In conflict tasks, accuracy for compatible trials is near-perfect, while fast responses on incompatible trials are often near (e.g., Wylie et al., 2009) or below (e.g., Stins et al., 2007) chance level. This pattern of erroneous responses is unlikely to be purely a result of fast-guessing, which would be expected to result in similar accuracy levels for both incompatible and compatible trials. Instead, these findings are consistent with the suggestion that erroneous responses are activated quickly via the direct processing route, before being selectively suppressed by an inhibitory control mechanism.

How response activation and suppression change as a function of response speed can also be seen in a *delta plot* (e.g., Burle et al., 2002; Ridderinkhof, 2002; Ridderinkhof et al., 2005; Wylie et al., 2010). This shows the size of the compatibility effect (RT on compatible trials subtracted from the RT on incompatible trials) as a function of RT (see **Figure 2C**). The plots make use of the whole RT distribution, rather than relying on a single measure of the central tendency, and therefore, they can reveal differences in the dynamics of response activation and suppression across individuals or groups even when mean RTs are not reliably different. Delta plots in traditional conflict tasks typically show initial positive effects that level off, or even become negative, as response times increase (e.g., de Jong et al., 1994; see also van den Wildenberg et al., 2010 for a review). This leveling-off is consistent with suppression of the unwanted stimulus-triggered response activation. As this suppression takes time to develop, a pattern of facilitation followed by inhibition is shown in the RT delta plot. Note however, that it is not necessary to postulate the existence of an active inhibitory mechanism which acts to selectively suppress inappropriately activated responses to explain the temporal dynamics of interference effects: the patterns shown in CAFs and delta plots may instead be produced by early activation of the inappropriate response which spontaneously decays over time (but see Burle et al., 2002 for evidence against this suggestion).

PRE-STIMULUS VS. POST-STIMULUS COGNITIVE CONTROL

Control mechanisms that can override inappropriate response plans which have been automatically evoked by the environment not only act to inhibit responses *after* they have been evoked by the stimulus. *Pre-stimulus* control mechanisms also seem to play a role. Thus, task set and previous experience can modulate conflicting response tendencies in a *preparatory* manner. Indeed, there is good evidence that pre-stimulus inhibitory mechanisms play a role in controlling responses in many contexts, including stop-signal (e.g., Verbruggen and Logan, 2009b), the anti-saccade (e.g., Everling and Munoz, 2000; Munoz and Everling, 2004), and reaction time tasks incorporating warning signals (e.g., Boulinguez et al., 2008).

The effects of pre-stimulus control have also been reported in traditional "conflict" tasks. Thus, the size of the congruency effect on the current trial in a conflict task can be modulated by (1) a pre-cue indicating whether the upcoming trial will be congruent or incongruent (e.g., Logan and Zbrodoff, 1982); (2) the ratio of congruent and incongruent trials in a block or experiment (e.g., Logan and Zbrodoff, 1979); and (3) whether the immediately preceding trial was congruent or incongruent (the so-called "Gratton effect" e.g., Gratton et al., 1988, 1992).

The Gratton effect has in particular been subject to much investigation. While some have suggested that it arises from repetition priming of exactly the same stimulus-response links from previous trials (e.g., Mayr et al., 2003), others have reported that it can occur without exact stimulus-response repetitions (e.g., Kerns et al., 2004; Akçay and Hazeltine, 2007). An influential *conflict monitoring hypothesis* proposed that following the response conflict experienced on an incongruent trial, cognitive control mechanisms which resolve this conflict are boosted for the next trial, in turn leading to reduced interference if the subsequent trial is also incongruent (e.g., Botvinick et al., 2001). This suggestions is supported by several observations that performance on incongruent trials is improved if they are preceded by another incongruent trial relative to a congruent trial (e.g., by Gratton et al., 1992 using Eriksen flankers; McBride et al., 2012 using object affordance; and by Stürmer et al., 2002 using the Simon task). However, this pattern has not consistently been reported and several researchers have documented selective benefits for compatible trials when the previous trial was also compatible (e.g., Kunde and Wühr, 2006; Akçay and Hazeltine, 2007; van Gaal et al., 2010a; Schlaghecken and Martini, 2011).

Schlaghecken and Martini (2011) recently accounted for these discrepant findings by suggesting that the effects of trial history on cognitive control were driven by a mechanism which responds to the previous experience of *both* the presence and the absence of conflict, arguing that the mechanism is one of *context* adaptation, rather than *conflict* adaptation. Whatever the mechanisms are that produce pre-stimulus control effects, it is clear that task set, instruction, and previous experience can modulate the apparently automatic priming of motor responses by visual objects.

UNCONSCIOUS CONTROL OVER UNWANTED RESPONSES

Traditionally, cognitive control mechanisms resulting in response inhibition have been considered as tightly coupled to consciousness (e.g., Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977, 1984), just as for voluntary control over actions. The logic behind this view is that observers need to be aware of the interfering, control-evoking, stimulus in order for control mechanisms to be implemented and for unwanted motor responses to be suppressed. Such a suggestion is supported by evidence from studies showing that inhibition of primed responses only operates when stimuli are presented above—and not below—the threshold required for conscious awareness (e.g., Merikle et al., 1995 using the Stroop task).

However, there is now increasing evidence that some forms of cognitive control can be executed entirely automatically, without conscious awareness—or volition. Some of the most compelling evidence for the automatic inhibition of unconsciously triggered motor priming comes from several experiments by Eimer and Schlaghecken (for reviews, see Eimer and Schlaghecken, 2003; Sumner, 2007). In their paradigm, participants typically made a speeded button-press response according to the direction of a target arrow, which was preceded by a masked (subliminal) prime. When the interval between mask and target was short (e.g., 20–40 ms), participants showed the expected speeding of responses when prime and target were compatible relative to when they were incompatible (positive compatibility effect, PCE). However, when the interval between prime and mask was extended beyond around 100–150 ms, incompatible trials produced faster responses than compatible trials. In other words, the usual priming effect had *reversed*.

This *negative compatibility effect* (NCE) has now been widely reported with button-press responses, foot responses, and eye movements (e.g., Eimer and Schlaghecken, 1998, 2002, 2003; Schlaghecken and Eimer, 2000, 2002; Eimer et al., 2002; Aron et al., 2003; Schlaghecken et al., 2003; Seiss and Praamstra, 2004; Sumner et al., 2007; Boy et al., 2008; Hermens et al., 2010), as well as in electroencephalogram recordings (e.g., Eimer and Schlaghecken, 1998, 2003; Praamstra and Seiss, 2005). They can also bias free-choice responses (e.g., Klapp and Hinkley, 2002; Schlaghecken and Eimer, 2004; Klapp and Haas, 2005), and have been shown both with familiar stimulus response mappings—such as arrows—and also when stimuli have been arbitrarily mapped to responses (e.g., Boy et al., 2008; Sumner, 2008).

Many researchers have suggested that this reversed priming results from an inhibitory mechanism in the motor system which acts to suppress sub-threshold motor activation evoked by the prime (e.g., Eimer and Schlaghecken, 1998; Klapp and Hinkley, 2002; Schlaghecken and Eimer, 2002; Schlaghecken et al., 2006). The most recent evidence suggests that such inhibition is triggered by the arrival of new stimuli—that the appearance of a second stimulus after the prime (normally the mask) automatically elicits an “emergency brake” that cancels any motor activation initiated by the prime (Jaśkowski and Przekoracka-Krawczyk, 2005; Lleras and Enns, 2006; Jaśkowski, 2007, 2008; Boy et al., 2008).

However, there has been considerable debate over whether the NCE genuinely reflects an inhibitory mechanism rather than arising from a purely perceptual process, or alternatively, from positive priming (PCE) of a motor response associated with elements of the mask stimulus. Perceptual accounts suggest that the NCE occurs because perceptual processing of the target stimulus is slower following a compatible prime, due to habituation-like processes such as “repetition blindness” or an attentional refractory period (Bavelier et al., 2000; Huber, 2008; Sohrabi and West, 2008; see also van Leeuwen and Lachmann, 2004, also discussed in Lleras and Enns, 2005 alongside the object updating theory; Hochhaus and Johnston, 1996; Huber et al., 2001, 2002; Johnston et al., 2002; Sohrabi and West, 2009). Such perceptual processes may play a role in producing some reversed priming effects, but they cannot account for more recent findings. For example, Boy and Sumner (2010) found that when participants learned novel sensorimotor associations in a masked priming task, and those response mappings were suddenly switched, both positive and negative priming effects temporarily reversed (see **Figure 3**)—indicating that the old response mappings continue to be primed until the participants learn the new mappings sufficiently well. Perceptual accounts of inverse priming cannot explain this finding.

Alternatively, perceptual interactions between the prime and the mask could end up causing motor priming in the opposite direction to that expected from the prime. This idea has been variously termed “object-updating,” “active mask,” or “mask-induced priming” (Lleras and Enns, 2004; Verleger et al., 2004; see Sumner, 2007 for review). Many early experiments used masks that were constructed by superimposing features in the alternative primes. In this case the most visually salient features of the mask could be those that were new onsets in the stimulus sequence—i.e., those that were not in the prime. Thus, the prime-mask sequence could actually prime the response opposite the one associated with the prime. Object updating may play a strong role in producing the NCE when masks are constructed from prime features, but they cannot account for the NCE in other cases where masks do not contain elements of possible primes (e.g., Sumner, 2008).

Overall, therefore, reversed priming effects can be caused in several ways. For the purposes of this review, the most interesting one is a form of automatic motor inhibition, which can be revealed with appropriate stimuli. Finding the NCE with subliminally presented primes provides evidence that the mechanisms at its origin are deployed automatically. If the observer is not aware of the prime, then presumably they cannot volitionally suppress any motor response associated with it. However, note that the prime does not necessarily need to be subliminal for the NCE to occur (e.g., Klapp and Hinkley, 2002; Klapp, 2005; Lleras and Enns, 2005; Mattler, 2005; Sumner et al., 2006; Schlaghecken et al., 2008).

AUTOMATIC INHIBITION IN THE AFFORDANCE PARADIGM

If the NCE shown in masked priming genuinely reflects an automatic control mechanism to suppress sub-threshold activation of an unwanted motor response (see above), one might expect to see evidence of an NCE in other paradigms where visual stimuli automatically evoke motor responses. Vainio and colleagues have recently reported that the positive stimulus-response compatibility effects usually shown in object affordance tasks can become *negative* if the object stimulus is presented briefly and then removed (e.g., Vainio, 2009; Vainio et al., 2011; see also Vainio and Mustonen, 2011).

This NCE-like effect was reported even when the prime stimulus (e.g., a cup) was not relevant to the on-going task (respond to direction of a subsequently presented target arrow), quite unlike the masked prime paradigm where primes typically need to contain elements relevant to the task for NCEs to be observed (e.g., Eimer and Schlaghecken, 1998). To account for this discrepancy, Vainio and colleagues suggested that even though the cup primes in their experiments were irrelevant to the participants’ task, a small degree of motor activation occurred due to the relatively long stimulus duration (compared to the primes in previous NCE studies), and the fact that the response association is highly over-learnt (compared to the semi-arbitrary correspondence between simple arrows or lines and a response). However, the associated motor activation was still sub-threshold, and thus able to be reversed by inhibition when perceptual support for that response was interrupted (producing the observed NCE). Overall, these studies suggest that actions which have been automatically primed by object affordances may also be subject to automatic control.

AUTOMATIC TRIGGERING OF “ENDOGENOUS” CONTROL

In the masked prime paradigm, the participants are not actually instructed to employ response inhibition—it just appears to occur

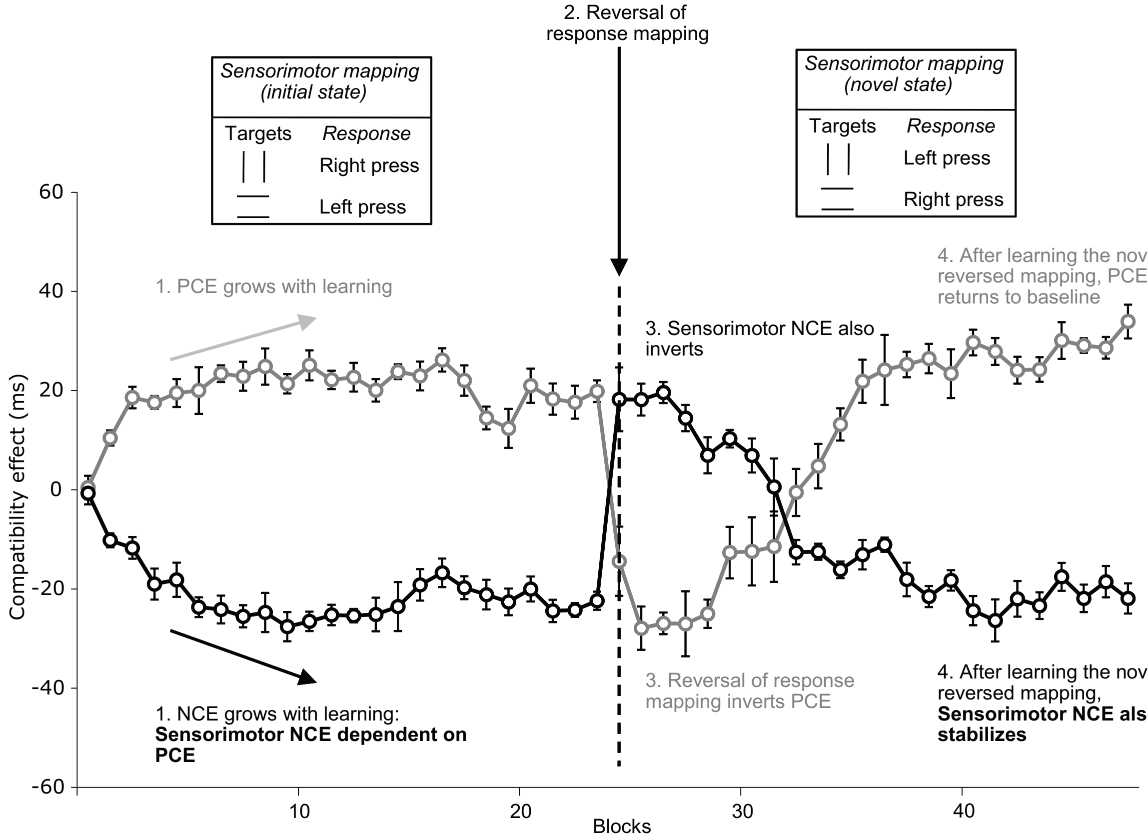

FIGURE 3 | Evolution of Positive and Negative Compatibility Effects following the sudden reversal of the response mapping in the paradigm used by Boy and Sumner (2010, Experiment 4). Participants were trained to respond to targets in a masked prime paradigm alternating short and long mask-target intervals by blocks of five trials. Figure adapted with permission from Boy and Sumner (2010). *J. Exp. Psychol. Hum. Percept. Perform.* 36, 892–905, originally published by the American Psychological Association.

automatically following the prime and mask. In other paradigms, participants are specifically asked to *endogenously* inhibit their planned motor responses when cued to do so, for example in the go/no-go task and stop signal task (e.g., Logan, 1994). In both tasks, participants are instructed to respond as quickly as possible to go-signals, but to withhold their response when other ("stop") stimuli occur.

Traditionally, such endogenous response inhibition has been thought to depend on the *conscious* detection of stop signals (e.g., Eimer and Schlaghecken, 2003). However, recent work suggests that endogenous suppression of pre-potent responses can also be primed or evoked unconsciously and automatically (e.g., Verbruggen and Logan, 2009a; van Gaal et al., 2008, 2009, 2010a,b). For example, van Gaal et al. (2009, 2010b) examined whether inhibition of a response could be triggered unconsciously by a *masked* stop-signal. They reported that although participants did not completely withhold their responses on unconscious (strongly masked) stop trials, they were significantly slowed relative to go trials, indicating there was some (incomplete) suppression of responses triggered by the imperceptible stop signal. Thus, the control processes involved in suppressing responses can be—at least partially—evoked by signals that are not consciously perceived.

AUTOMATIC PRE-STIMULUS CONTROL

In the case of both the NCE and the "endogenous inhibition" paradigms discussed above, inhibitory control processes appear to be evoked to deal with motor activation after it has been elicited. Is it also possible that pre-stimulus preparatory types of control can be elicited automatically? Many researchers have suggested that observers must consciously experience conflict in order for the pre-stimulus control mechanisms to be deployed (e.g., Kunde, 2003; Mayr, 2004; Ansorge et al., 2011). However, recent evidence from van Gaal et al. (2010a) suggests that some pre-stimulus control can be evoked automatically, without conscious awareness (see **Figure 4**). They used a meta-contrast masking paradigm to manipulate awareness of conflict-inducing stimuli. Conflict between co-activated responses was either conscious (weakly masked primes) or unconscious (strongly masked primes). The largest conflict adaptation effects occurred when both the current and the previous trial were weakly masked (visible). Importantly, a small but statistically significant conflict adaptation effect was evident when primes on trial *n* and trial *n–1* were both presented below the threshold required for conscious awareness (strongly masked condition). This is consistent with the suggestion that unconsciously presented stimuli can automatically evoke these pre-stimulus conflict adaptation mechanisms,

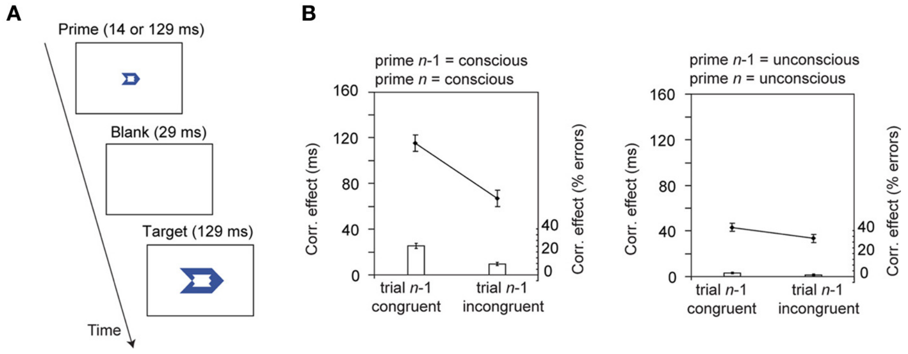

FIGURE 4 | Automatic (unconscious) conflict adaptation effects as shown in van Gaal et al. (2010a). Observers responded to the direction of a target arrow stimulus that had been preceded by a backwards (meta-contrast) masked prime that either corresponded with the response required to the target (as shown in **A**), or was non-corresponding. The prime stimulus was either conscious (presented for 129 ms) or unconscious (presented for 14 ms). Correspondence effects (non-corresponding—corresponding) on trial *n* were modulated by whether trial *n*–1 was corresponding or not. These effects were largest when both trial *n* and trial *n*–1 had visible primes **(B)**, but were still significant when both trial *n* and trial *n*–1 contained invisible primes. These figures were originally published in van Gaal et al. (2010a). *PLoS One* 5:e11508. doi: 10.1371/journal.pone.0011508.

and can modulate the effects of subsequent conflicting stimuli. However, this result should be interpreted cautiously because responses are typically faster following fast responses (congruent trials), and slower following slow responses (incongruent trials; see e.g., Laming, 1979). If this effect were more apparent on fast (congruent) trials than on slow (incongruent) trials then it might entirely account for the small Gratton effect observed with non-conscious stimuli.

OVERLAP BETWEEN BRAIN AREAS RESPONSIBLE FOR AUTOMATIC AND VOLUNTARY CONTROL

The traditional distinction drawn between automatic and voluntary cognitive control is not only being challenged by behavioral studies. Lesion and imaging studies have also revealed substantial overlap between brain regions traditionally associated with "voluntary" control and those active during automatic control. Brain areas in medial frontal cortex such as the SMA and anterior cingulate cortex (ACC) have traditionally been considered to be important for *voluntary* control (for a review, see Nachev et al., 2008). However, they also seem to be involved in mediating *automatic* motor activation and suppression of unwanted action plans (e.g., D'Ostilio and Garraux, 2011, 2012). For example, Sumner et al. (2007) used a masked prime paradigm to reveal that two extremely rare patients with microlesions of the SMA and/or the adjacent supplementary eye field (SEF) showed normal PCEs but failed to show NCEs, unlike healthy matched controls. These data are consistent with the view that the SMA and SEF may play causal roles in producing the *automatic* motor inhibition indexed behaviorally by the NCE. Thus, areas involved in the voluntary control of action might play a crucial role in automatic inhibition of unwanted actions (in this case, evoked by the subliminal prime).

There is also evidence from healthy observers that the SMA and nearby pre-SMA are involved in producing the unconscious NCE in healthy observers. Recent research from van Gaal et al. (2011b), found that individual differences in pre-SMA gray matter density were correlated with participants' ability to correctly respond to a target that had been preceded by a strongly masked (invisible) incompatible prime. Furthermore, Boy et al. (2010a) found that the fMRI signal was modulated by (invisible) prime compatibility in the SMA. Moreover, by studying normal participants' *in vivo* neurochemistry through magnetic resonance spectroscopy (MRS), Boy et al. (2010a) found that for a region including the SMA, the measured concentration of gamma-aminobutyric acid (GABA)—the main neurotransmitter responsible for neuronal inhibition—was correlated with the magnitude of the NCE.

There is also overlap between "voluntary" and "automatic" neural mechanisms involved in more conventional inhibition tasks such as go/no-go, and stop signal paradigms. van Gaal et al. (2010b) found that the amplitude of a fronto-central N2 event-related potential (ERP) component was reliably correlated with successful stopping on weakly masked (conscious) stop trials, and with the amount of slowing on strongly masked (unconscious) stop trials (as measured by the stop signal reaction time; SSRT). Thus, the size of this N2 component correlated with behavioral measures of both conscious and unconscious suppression of response. In addition, functional imaging has shown that strongly masked no-go signals activate much of the same brain areas that are activated by weakly masked no-go signals, particularly the pre-SMA and inferior frontal cortex (van Gaal et al., 2010b). The strength of activation in these areas was positively correlated with the amount of slow-down on strongly masked no-go trials—which supports the suggestion that this activity may be functional and have a direct effect on stopping behavior.

Taken together, these findings challenge the traditional assumption that voluntary control and involuntary mechanisms occur through distinct pathways in the brain. Rather, there is considerable overlap between the brain regions which are active during consciously and unconsciously triggered action control.

DISSOCIATIONS IN AUTOMATIC AND VOLUNTARY CONTROL

Recent work from Boy et al. (2010b) suggests that the important distinction is not between control that is automatic compared

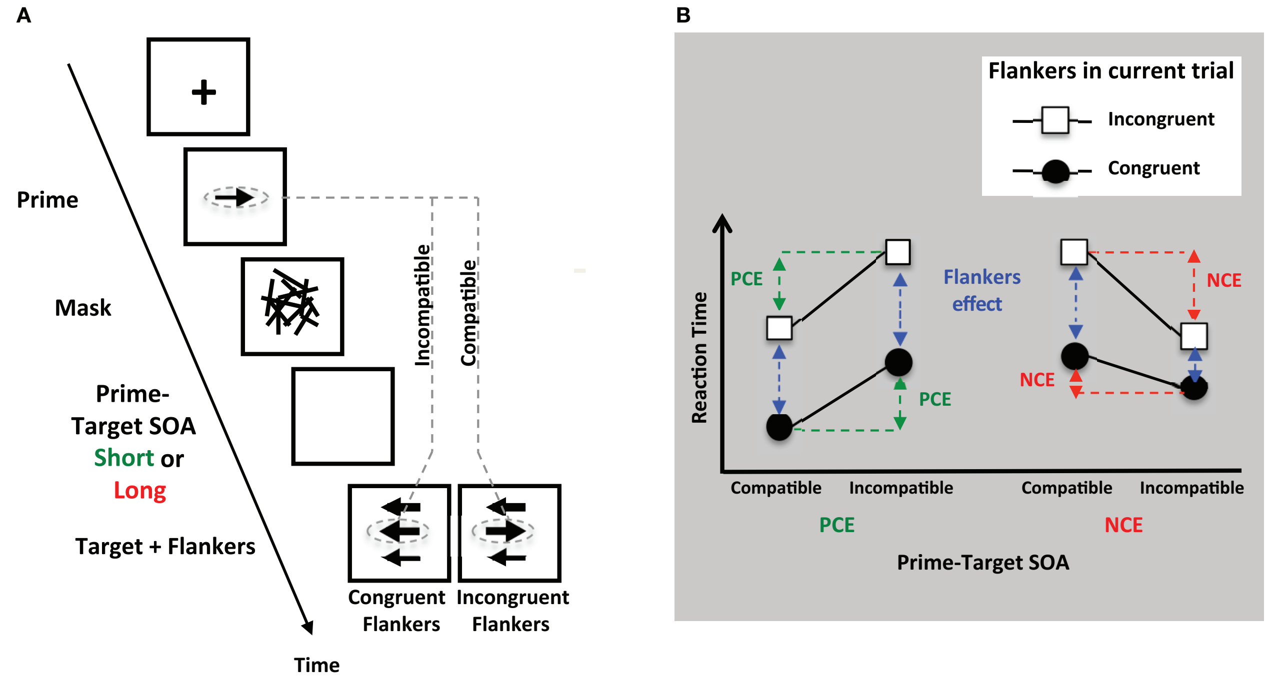

FIGURE 5 | (A) Schematic illustration of the task in Boy et al. (2010b), which combines subliminal priming and flanker interference. If the stimulus onset asynchrony (SOA) between prime and target (response) cue is short (70 ms), a PCE in response times is found (green arrows in **B**). If the SOA is longer (180 ms), an NCE is found (red arrows in **B**). Compatibility refers to whether the direction of prime arrow and target (response) arrow is the same (compatible) or different (incompatible). Targets are flanked by arrows. If the flankers are congruent with the target, then response times are shorter than if flankers are incongruent (the flanker interference effect; blue arrows in **B**). 4-B. Results: for positive priming (PCE), the priming effect was additive with the effect of flanker interference. For the NCE, which measures subliminal inhibition, there was an interaction with flanker interference. This interaction did not occur for pre-stimulus control [data not shown here, see Boy et al. (2010b)].

to control that is voluntary, but rather between *pre-* and *post-stimulus* control (see discussion above on pre- vs. post-stimulus control). These investigators used a hybrid task which integrated masked priming into an Eriksen flanker paradigm (see **Figure 5A**). They showed an interaction between the *post-stimulus* inhibitory influences caused by prime-mask sequence (the NCE) and the post-stimulus control of flanker interference. Thus, these processes presumably share some common mechanisms (see **Figure 5B**). However, when examining the influence of the previous trials' flankers on performance in the current trial (the Gratton effect, see section on pre-stimulus control), no such interaction was found with the NCE. This suggests that pre-stimulus control mechanisms did not share processes with the NCE, and thus are distinct from post-stimulus mechanisms.

FLEXIBLE AUTOMATICTY

Automatic and unconscious processes are traditionally regarded as inflexible (e.g., Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977, 1984), quite distinct in quality from the flexible nature of "voluntary" processes. However, there is increasing evidence that automatic and subliminal processes can in fact be modulated by "top-down" processes of attention, intention ("task set" or current goals) and expectation. For example, Kentridge and colleagues (e.g., Kentridge et al., 1999, 2004, 2008) have reported a series of studies in which attention modulates apparently subconscious processing, both in a "blindsight" patient, GY, and in normal participants. Focussing attention in time (e.g., Naccache et al., 2002) and in space (Lachter et al., 2004; Sumner et al., 2006; Marzouki et al., 2007) can also modulate the effects of masked primes on motor responses. For example, positive and negative compatibility effects in a masked prime task can be enhanced by exogenously pre-cueing prime location (Sumner et al., 2006), and in such a way that was not simply explained by an attentional boost to the perceptual strength of the prime. This suggests that attention does not only enhance perceptual processing, but can also modulate sensori-motor linkages.

Task set-up and instruction can also modulate many of the effects of visual stimuli on motor responses and control. As noted above, prime stimuli in masked priming tasks generally only affect responses when they share task-relevant elements with the target stimuli (e.g., Eimer and Schlaghecken, 1998; see also Huang et al., 2011). For example, Eimer and Schlaghecken (1998) found no NCE when participants responded to letter targets that had been preceded by masked arrow primes, even though arrow primes reliably prime responses when targets are also arrows. Moreover, recent evidence shows that object affordance effects are also dependent on the goals of the observer. Bub and Masson (2010) demonstrated that the handle of a mug only produced reliable affordance effects on reach and grasp responses, not when the response was made via a speeded button press.

Unconscious "endogenous" control over responses also depends on task instruction. Wokke et al. (2011) tested participants with a go/no-go task in which a masked (unconscious) prime stimulus preceded an unmasked (conscious) target. One of two possible targets was presented on each trial, but unlike other studies, stimuli were not consistently paired with either a "go" or a "no-go" response across a testing session. Instead, which of the possible targets required a "go" or a "no-go" response was cued on a trial-by-trial basis. Response inhibition rates were improved when a "no-go" target was preceded by an invisible "no-go" cue. As the instruction cue manipulation eliminated any long-term associations being built up between stimulus and response, it seems that control processes evoked by unconsciously presented stimuli can be triggered in a flexible manner according to task instruction.

Finally, pre-stimulus, conflict adaptation effects such as the Gratton effect can also be modulated, seemingly by reward (van Steenbergen et al., 2009). For example, van Steenbergen and colleagues (2009) showed that the conflict adaptation effect in a flanker task can be reduced by reward, even though rewards were given arbitrarily and were unrelated to the task. In fact Botvinick (2007) has recently suggested that conflict might be experienced as a negatively reinforcing event. As such, it is possible for the effects of conflict (a negative stimulus) to be counteracted by a positive stimulus (reward)—an example of possible flexible control over an automatic response.

Taken together, these findings indicate that seemingly "automatic" response activation and control can be implemented flexibly—quite unlike the traditionally inflexible view of automatic processes.

CONCLUSION

The evidence described in this review demonstrates that stimuli can automatically prime specific, purposeful actions. Simple stimuli can capture eye movements, produce activity in motor-related brain areas, and can trigger the actions afforded by an object. Because observers are constantly bombarded by a complex set of visual stimulations, such automatic activation of potential responses is likely to be important, either in facilitating responses or requiring inhibition so other responses can be made. While their effects might not be obvious in healthy adults, the effects of such automatic activation of motor programs can be dramatically revealed following brain damage (e.g., in alien limb syndrome or utilization behavior).

A necessary pre-requisite for flexible, goal-directed action is the ability to inhibit inappropriate, competing, responses even when those competing responses have been activated automatically. Cognitive control has traditionally been seen as tightly coupled to awareness, it has been suggested that an observer must be aware of a stimulus in order to inhibit motor activation evoked by that stimulus. Many of the findings reviewed here challenge this assumption and instead suggest there is substantial overlap between the mechanisms supporting conscious and unconscious control of responses. Thus, we suggest that while there may be differences between automatic and voluntary control, they may not be entirely distinct in the brain, that automatic processes may play a role in all behavior, and that we must revise traditional views that couple cognitive control to consciousness and automaticity to inflexibility.

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Is consciousness necessary for conflict adaptation? A state of the art

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Facing response conflict, subjects try to improve their responses by reducing the influence of the detrimental information which caused the conflict. It was speculated that this adaptation to conflict can only occur when the conflicting information is consciously perceived. In this review we give an overview of the research looking at the possibility of unconscious stimuli to provoke this conflict adaptation. In a first part we discuss adaptation to conflict on a trial-by-trial basis. When the previous trial contained conflicting information, subjects will adapt to this by reducing the influence of the conflicting information on the current trial. However, the interesting question is whether this is also possible when the conflicting information remains unconscious. In a second part we will discuss blockwise adaptation to conflict. If conflict is very frequent, subjects will adapt to this by reducing the conflicting information sustainably. Again the question is whether this is possible when the conflict was never experienced consciously. In a third part we will discuss the neural basis of conscious and unconscious conflict adaptation. We will critically discuss the research on these topics and highlight strengths and weaknesses of the used paradigms. Finally, we will give some suggestions how future research can be more conclusive in this respect.

Keywords: unconscious perception, conflict adaptation, cognitive control

INTRODUCTION

A hot topic in cognitive psychology nowadays is the question whether cognitive control can be exerted unconsciously. One typical expression of cognitive control is adaptation to response conflict. It has been convincingly shown that subjects adapt to conflicting information, by reducing the influence of this irrelevant information. The interesting question here is whether this is also possible when the conflict itself remains unconscious. Since much cognitive processing seems to be possible without any intervention of consciousness, this is an intriguing question. In this review we will give a clear overview of studies addressing this issue, and elaborate on contradictory findings in the field.

THE POWER OF UNCONSCIOUS PROCESSING

One of the most challenging questions in cognitive psychology is what defines the role of consciousness. As Lau (2009) points out, humans feel that without consciousness we would only be able to perform simple, reflexive behavior. Intuitively, we claim that we need consciousness to execute complex behavior based on our conscious intentions. Most people would agree that consciousness has an important function in life, although it is difficult to spell out what it is precisely. However, the answers from science are not unequivocal. An overwhelming body of research has shown that many cognitive processes can occur without consciousness meddling in. Yet this consensus is a very recent one. It has long been a spirited topic of debate whether stimuli which do not pass the consciousness threshold can be processed at all. Skeptics claimed that almost all research failed to assure that stimuli were truly unconscious (e.g., Eriksen, 1960; Holender, 1986) and false claims about subliminal advertising did more harm than good (Pratkanis, 1992). But with methodological improvements, such as better masking paradigms (Evett and Humphreys, 1981; Forster and Davis, 1984) and objective prime awareness tests (Greenwald et al., 1996) to ensure the unconscious nature of the stimuli, the consensus grew that stimuli which never enter our consciousness are nevertheless capable of influencing on going behavior (Kouider and Dehaene, 2007). Not only is the existence of unconscious perception no longer questioned, accumulating evidence has highlighted the potentially far-reaching power of unconscious processing.

Unconscious semantic activation

Much research on unconscious processing made use of the priming paradigm. In this paradigm subjects have to respond to a target which is preceded by an irrelevant prime. Responses to this target are faster when it is preceded by a prime which triggers the same response as the target (i.e., a congruent prime) compared to a prime which triggers a different response (i.e., an incongruent prime). This congruency effect is a robust phenomenon both when the prime is clearly visible and when it is masked (e.g., Vorberg et al., 2003). Initially, it was assumed that masked, invisible stimuli could only trigger automatic response priming. For example, Eimer and Schlaghecken (1998) showed that a prime arrow, which is displayed for only 16 ms, is capable of activating motor responses. Dehaene et al. (1998) went one step further and found that a subliminally presented prime number facilitated responses to a target number when they shared a semantic relation, suggesting that unconscious stimuli can be processed up to a semantic level.

Although this semantic interpretation was not generally accepted at first (Damian, 2001; Kunde et al., 2003), there have been convincing studies which showed that a subliminal prime is indeed capable of influencing the reaction to a target via their semantic relation (Van den Bussche et al., 2009a; Van Opstal et al., 2010). A meta-analysis on masked priming studies (Van den Bussche et al., 2009b) confirmed that even when all non-semantic influences are excluded, subliminal primes can still evoke priming effects. So, unconscious primes can reach a high semantic processing level. Following the explanation by Dehaene et al. (1998) we assume that these masked priming effects are the consequence of conflict at the response level. On congruent trials, the prime activates the same response as the target, whereas on incongruent trials both sources active a different response, and this response conflict slows down responding (for a different view see Kinoshita and Hunt, 2008).

Top-down influences on unconscious processing

Next to being able to reach semantic processing levels, the effect of subliminal stimuli is not restricted to purely bottom-up processing. Although the influence of unconscious primes has often been thought a static, uncontrollable process, recently research pointed out that it can be influenced by top-down aspects such as task demands (Norris and Kinoshita, 2008; Martens et al., 2011), attentional focusing (Van den Bussche et al., 2010), and temporal attention (Naccache et al., 2002). Martens et al. (2011) used an induction task to activate one of two task sets. Subjects had to decide whether pictures of objects where living or non-living (i.e., a semantic induction task) or whether they were round or elongated (i.e., a perceptual induction task). This induction task had an influence on a subsequent priming task. After the semantic induction task priming was only observed when prime and target shared a semantic relationship, but not when they only shared a perceptual relationship. After the perceptual induction task the opposite was true. Likewise, Norris and Kinoshita (2008) showed in a masked priming task that the priming effect for non-words was dependent on the task. In a standard lexical decision task, no unconscious priming for non-words was observed. However, when exactly the same prime–target pairs were used, but now the task was to decide whether the target was the same as a probe, unconscious priming was also observed for non-words. Van den Bussche et al. (2010) showed that spatial attention is a prerequisite for subliminal stimuli to be processed. When attention was allocated to another location, primes had no influence on the processing of the target. In a similar vein, Naccache et al. (2002) demonstrated that subliminal primes only influenced responses to targets when temporal attention was allocated to the time window in which the prime appeared. When this was not the case, no priming effects emerged.

These studies illustrate that subliminal priming is not an inflexible process which operates in a purely automatic, bottom-up fashion. Our conscious preparation can have large modulating effects on the processing of unconscious primes (e.g., Kunde et al., 2003).

THE LIMITS OF UNCONSCIOUS PROCESSING

As described above, accumulating evidence shows that unconscious stimuli can be processed upto a high semantic level, and that it is susceptible to several conscious top-down modulations. Over the years the consensus grew that many mental activities can be performed without awareness, and the intriguing question arose which processes require consciousness. Does unconscious processing have limits and does consciousness have a special function at all? A controversial position on this topic was taken by Libet (1985) who speculated that consciousness and free will are illusory (see also Wegner, 2002). He showed that the brain activation of an action is present in the electroencephalogram (EEG) waveform, several hundreds of milliseconds before the subject has the conscious experience of initiating the action. Recently this finding was extended by Soon et al. (2008) who showed that the decision to perform an action was measurable in prefrontal and parietal cortex, up to 7 s before subjects consciously decided to act. So it seems that consciousness has nothing to do with initiating actions, but subjects only *post hoc* create the illusion that they deliberately produced the action.

Contrary to this extreme position, Dehaene and Naccache (2001) argued that there are borders which determine the potential role of unconscious processing. They proposed a framework in which specialized modular systems can process stimuli without conscious amplification, as long as this is merely a bottom-up process which requires no strategic adaptation. This bottom-up processing of unconscious stimuli can be altered by the processing state of our cognitive system, such as the focus of attention or the currently activated task set, as long as this is initiated consciously. What should, however, not be possible, is for an unconscious stimulus itself to change these top-down strategies of participants. Unconscious processing can only use these purely bottom-up modular systems in the brain. According to Dehaene and Naccache (2001), without global ignition (which is the determinant of consciousness) these stimuli cannot initiate top-down cognitive control, because they remain within a modular system. According to this proposal, consciousness should be exclusively associated with strategic operations such as planning a new strategy, evaluating it, controlling its execution and correcting possible errors. All these operations can be grouped under the term *cognitive control.*

If we want to test whether consciousness is more than just an epiphenomenon without any purpose, it is necessary to capture those behaviors which cannot be initiated by unconscious stimuli. Focusing on cognitive control operations might offer a fruitful approach to explore this debated issue, since they have been specifically associated with consciousness (Dehaene and Naccache, 2001). This is of course not an easy task to accomplish, because we are looking for the *absence* of an effect, and this can almost always be explained by alternative interpretations. Thus we need convincing research which is completely free from methodological flaws, to be able to answer this question.

COGNITIVE CONTROL AND CONFLICT ADAPTATION

Because cognitive control is not a well-defined area of human actions, it is important to specify the behavior under investigation.

Many different behaviors are categorized under the term cognitive control, and most definitions are very broad. For example, Botvinick et al. (2001) defined cognitive control as the human cognitive system's "ability to configure itself for the performance of specific tasks through appropriate adjustments in perceptual selection, response biasing, and the on-line maintenance of contextual information" (p. 624). Although exhaustive, we risk that with such a general definition, in the end, almost all behavior is an instance of cognitive control. Therefore in this review we will focus on one commonly investigated expression of cognitive control, namely the ability to detect response conflict and adjust our behavior accordingly. It should be stressed that research on unconscious processing was also carried out in other domains of cognitive control. Typically, it is found that instances of cognitive control can be influenced unconsciously, if subjects are familiarized with the conscious variant of the task before. For example, if subjects have learned to withhold a response when a visible stop-signal is presented, responses will also slow down when this stop-signal is presented unconsciously (e.g., van Gaal et al., 2010a,c). Likewise, if subjects have learned which task to perform dependent on a task cue, the task can be primed by presenting the corresponding cue unconsciously (Lau and Passingham, 2007; De Pisapia et al., in press; Reuss et al., 2011). Finally, post-error slowing can occur, even when subjects are completely unaware of making an error (Hester et al., 2005; Cohen et al., 2009). Thus, although detecting response conflict and adjusting our behavior accordingly is a commonly investigated expression of cognitive control, others also exist.

A typical example of *conflict adaptation* can be found in the Stroop task, where subjects are confronted with color words (e.g., green) which are printed in a color that can either match the word meaning (e.g., green; a congruent situation) or not match the word meaning (e.g., red; an incongruent situation). Subjects are asked to name the ink color (i.e., the relevant information) as fast as possible, while ignoring the word meaning (i.e., the irrelevant information). In an incongruent situation both sources of information trigger differential responses, and thus create response conflict, which slows down responding. Consequently, responses are usually much faster in the congruent condition than in the incongruent condition (i.e., the congruency effect). This response conflict can occur in all tasks in which relevant and irrelevant information can potentially activate differential responses. To prevent this irrelevant information to exert the same detrimental influence later on, our cognitive system will adapt to this conflict so that in a subsequent conflict situation we are better in dealing with the conflict, and thus in reducing its detrimental influence. It was proposed that the cognitive system adapts to this response conflict by inhibiting the irrelevant information (Stürmer et al., 2002) or by narrowing attention to the relevant information (Egner and Hirsch, 2005). Wühr and Frings (2008) showed in a within-trial paradigm that target amplification and distractor suppression presumably interact in selecting the correct answer. Because the precise mechanism of conflict adaptation remains debated, we prefer to remain theoretically neutral when using this term. Throughout this review, we will use the term conflict adaptation to refer to the behavioral effects following response conflict. Likewise, although other kinds of conflict exist, our focus lies on response conflict. Thus, when using the term conflict we are referring to response conflict.

We can dissociate two strategies to cope with this kind of response conflict. We can handle the conflict on a trial-by-trial basis and adjust our response strategy according to the conflict in the current trial (i.e., micro-adjustments; Ridderinkhof, 2002). Alternatively we can pick up regularities over a longer period of time and adjust our strategy blockwise, based on this accumulated information (i.e., macro-adjustments; Ridderinkhof, 2002).

The next section is divided into two parts in which we will discuss these trial-by-trial and blockwise strategies separately. After a brief overview of the literature we will elaborate on experiments investigating the (im)possibility of unconscious conflict to cause these kinds of conflict adaptation.

AN AREA EXCLUSIVELY RESERVED FOR CONSCIOUSNESS?

CONFLICT ADAPTATION ON A TRIAL-BY-TRIAL BASIS

The strategy to cope with response conflict on a trial-by-trial basis was explored by Gratton et al. (1992) with the Eriksen flanker task (Eriksen and Eriksen, 1974). In this task subjects have to respond to a central target letter (A or H). This target letter is flanked by irrelevant distractor letters. These distractors can trigger the same response as the target letter (i.e., a congruent situation; AAAAA) or they can trigger the opposite response (i.e., an incongruent situation; HHAHH). Although the distractor letters are completely irrelevant for the task, they nevertheless exert a great influence; large congruency effects are observed under these conditions. Interestingly, the authors observed that the congruency effect was modulated by the congruency on the previous trial. If there was conflict (i.e., an incongruent trial) on the previous trial, they observed a smaller congruency effect on the current trial, compared to when the previous trial was congruent. This implies that subjects, facing conflict, adapt to this conflict by reducing the source of the conflict (the irrelevant information) on the following trial. Thus although subjects are not able to simply ignore the irrelevant information throughout the whole task, they nevertheless adapt their behavior on a trial-by-trial basis based on this irrelevant information.

These sequential modulations have also been shown in other paradigms such as the Stroop task (Kerns et al., 2004; Notebaert et al., 2006; Lamers and Roelofs, 2011), the Simon task (Stürmer et al., 2002; Akçay and Hazeltine, 2008; Verguts et al., 2011), and the priming paradigm (Kunde, 2003; Kunde and Wühr, 2006). Apparently it does not matter whether conflict is conveyed by an irrelevant flanker, an irrelevant word meaning, an irrelevant position, or an irrelevant arrow (for a different view, see Egner, 2008). Whenever the cognitive system detects conflict it will adapt to it and reduce the influence of the irrelevant information on the next trial.

UNCONSCIOUS CONFLICT ADAPTATION ON A TRIAL-BY-TRIAL BASIS

The previous part made it clear that subjects cope with conflict on a trial-by-trial basis by reducing the influence of the irrelevant information on the following trial. The interesting question now is whether this adaptation also occurs when the conflict itself remains unconscious (see **Table 1** for an overview of studies addressing this

Table 1 | Schematic overview of studies looking at adaptation to conflict on a trial-by-trial basis.

	Condition	Prime	Blank	Backward mask	Blank	Target	Adaptation to conflict
Greenwald et al. (1996)	Conscious	SARAH 50	▨	17	83	MIKE	+
	Unconscious		▨	PDGFYBYLG 17			−
Kunde (2003)	Conscious	 128	28	▨	▨	 126	+
	Unconscious	 14		▨	▨		−
Frings and Wentura (2008)	Conscious	Holiday 60	▨	▨	▨	HAPPY	+
	Unconscious	Holiday 40	▨	GJKLVWCP 20	▨		−
van Gaal et al. (2010b)	Conscious	 129	28	▨	▨	 129	+
	Unconscious	 14		▨	▨		−
Ansorge et al. (2011)	Conscious	above 34	▨	34	▨	BELOW 200	+
	Unconscious		▨	GYCHGLTAD 17			−

Gray boxes indicate the absence of the particular feature in a study, empty boxes indicate a blank. The numbers in the right corners indicate the duration in milliseconds.

issue). To answer this question, Kunde (2003) used a meta-contrast masking paradigm. In this paradigm a prime arrow fits perfectly in the target contour, so that this first arrow is rendered invisible if both are presented in short succession. To create conscious and unconscious conditions, the prime duration was randomly varied between 14 and 126 ms, followed by a blank of 28 ms. Independent of the prime duration on the current trial, Kunde found a reduction of the congruency effect only when a 126 ms prime was presented on the previous trial (similar results were presented by Greenwald et al., 1996). Based on this observation, he concluded that we can only adapt to conflict on a trial-by-trial basis when this conflict is consciously experienced. An important problem with this study is that the prime duration differed between the conscious and unconscious conditions. This changed the time between the onset of the prime and the onset of the target stimulus onset asynchrony (SOA) which is sufficient to influence priming effects (Eimer and Schlaghecken, 1998).

In an affective priming experiment Frings and Wentura (2008) held the SOA fixed at 60 ms. On every trial they presented a prime word with a positive or negative valence, followed by a target word which could be either congruent (i.e., the same valence) or incongruent (i.e., the other valence) with the prime. In the conscious condition the prime was presented 60 ms, without a mask. In the unconscious condition the prime was only presented 40 ms followed by a 20 ms post-mask. Replicating Kunde (2003) they found a sequential modulation of the congruency effect on the current trial only when an unmasked prime was presented on the previous trial.

Contrary to the these studies, which indicate the impossibility of unconscious conflict to alter the processing of the next trial, van Gaal et al. (2010b) challenged the hypothesis that conflict which remains unconscious can never recruit top-down cognitive control. They used the same experiment as Kunde (2003), but omitted a brief auditory warning signal at the beginning of each trial and shortened the inter-trial interval. Contrary to Kunde (2003) they observed conflict adaptation on the current trial, independent of the visibility of either the current or the previous trial. According to the authors, the auditory signal in the study of Kunde (2003) disturbed subjects' attention and thereby wiped out any unconscious traces. Two recent studies also claimed to have found adaptation to unconscious conflict. In a priming study, Francken et al. (2011) obtained conflict adaptation on the current trial, independent of the visibility of the previous trial. However, this was only the case in the error rates, not in reaction times. Moreover, the visibility of their low-visibility condition was too high to be considered unconscious. Bodner and Mulji (2010) presented only masked primes, and manipulated conflict frequency. For half of the participants 80% of the trials were congruent, for the other half 80% of the trials were incongruent. A larger priming effect for the group receiving 80% congruent trials was only apparent when the previous trial was incongruent or neutral. When the previous trial was positive, no different priming effects were observed. Although this shows that congruency effects are dependent on the congruency of the previous trial, these results are qualitatively different from those presented by van Gaal et al. In the group receiving 80% incongruent trials, Bodner and Mulji (2010) observed numerically smaller congruency effects following incongruent trials. However, in the group receiving 80% congruent trials, the congruency effect was numerically *larger* following an incongruent, compared to a congruent trial. This observation is unexpected, and it is currently unclear how this can be reconciled with the findings of van Gaal et al.

ALTERNATIVE EXPLANATIONS

Based on the studies of van Gaal et al. (2010b) and Francken et al. (2011) one could conclude that unconscious conflict can trigger adaptation behavior. An important question is whether these results are truly the consequence of unconscious conflict, or alternatively the consequence of information which reached consciousness (e.g., Ansorge et al., 2011). For example it is possible that van Gaal et al. (2010b) found unconscious conflict adaptation, not because the conflict exerted an influence on behavior unconsciously, but because participants became somehow aware of the conflict on a meta-cognitive level (e.g., Van den Bussche et al., 2008). For example, responses are typically slower on incongruent trials, and perhaps subjects became consciously aware of this reaction time slowing. It has been shown that subjects can reliably "read out" their own reaction times in a conscious manner (Corallo et al., 2008; Marti et al., 2010). Perhaps adaptation on the current trial can be triggered by the conscious experience that we somehow responded slower on the previous trial. Another way in which we can consciously experience differences on the previous trial is because of different senses of control. Recently, in a masked priming study it was shown that our sense of control over action effects (i.e., a stimulus presented after responding) is larger when the effects are produced by congruent compared to incongruent trials (Wenke et al., 2010). Thus, although subjects are never consciously aware of any prime, they nevertheless feel more in control over the effects of congruent compared to incongruent trials. A similar possibility is that subjects consciously experienced that responding was somehow easier on congruent than on incongruent trials, although the reason for this experience remained unconscious. In this case, subjects adapted their behavior on the current trial, based on the consciously experienced *difficulty* of the previous trial, rather than the unconscious *conflict* of the previous trial (e.g., Kinoshita et al., 2011).

This last point was also noted by Ansorge et al. (2011). In their priming experiment, all primes were followed by a 34 ms blank or a 34 ms mask, to create conscious and unconscious conditions. To control for meta-cognitive explanations of sequential modulations, they collected visibility data on a trial-by-trial basis. After every trial, participants were asked whether they had just encountered a congruent or an incongruent trial. When the authors analyzed only those trials on which subjects *wrongly* judged the congruency of the previous trial, no sequential modulations were found at all. This suggests that even in the unmasked condition conflict awareness plays a major role. When they analyzed only trials in which subjects correctly identified the congruency of the previous trial, they observed sequential modulations dependent on the congruency of the previous trial, only when the conflicting information on the previous trial was unmasked. This suggests that unconscious trial-by-trial adaptations cannot be caused by subjects becoming aware of the conflict on some level. However, also this conclusion is premature. The main advantage of this trial-by-trial assessment is that we can determine whether unconscious trial-by-trial adaptations can be caused by responses on those trials where subjects, despite the masking, were consciously aware of the prime or the prime–target congruency on the previous trial. Importantly, these trials should be distinguished from trials on which subjects really had no idea about the congruency at all, because in the latter case an unconscious sequential modulation effect cannot be explained by meta-cognitive processes. Unfortunately Ansorge et al. (2011) gave participants only two response options in the visibility question ("was the trial you just saw congruent or incongruent?"). In this way, a confound exists between genuine judgments and instances in which subjects really had no idea and just guessed. This can conceal a possible unconscious conflict adaptation effect.

CONCLUSION

In summary, although van Gaal et al. (2010b) and Francken et al. (2011) recently observed adaptation to conflict on a trial-by-trial basis, even when the conflicting information on the previous trial was masked, it would be premature to conclude that sequential modulations can be initiated by unconscious conflict. Research on sequential modulations has repeatedly shown that subjects only adapt to conflict on the previous trial, when this conflict was experienced consciously. Furthermore, an alternative meta-cognitive explanation can be readily offered for the findings of van Gaal et al. In the Section "General Discussion" we will discuss the conditions required to investigate this unresolved issue further.

AN AREA EXCLUSIVELY RESERVED FOR CONSCIOUSNESS?

BLOCKWISE ADAPTATION TO RESPONSE CONFLICT

The second strategy described by Ridderinkhof (2002; macro-adjustments) to adapt to conflict is based on detecting blockwise regularities of conflict trials. This is a useful strategy when, for example, congruency proportions are manipulated. If in a block the proportion of incongruent trials is much larger than the proportion of congruent trials, the level of conflict is generally elevated. Since in this situation most trials contain conflict, the most economical strategy is probably to simply reduce the detrimental influence of the irrelevant information continuously. This strategy is adequate for most trials and thus seems an acceptable way to deal with the conflict. Adapting our behavior on a trial-by-trial basis according to the conflict on the previous trial is also a potential strategy here, but this would be much more cognitively demanding because the majority of trials contain response conflict and the cognitive system would have to reduce the influence of the irrelevant information repeatedly. Instead, it would be much easier for the cognitive system to simply reduce the influence of the irrelevant information sustainably. There is much evidence that subjects effectively deal with these blockwise statistical regularities. For example Logan and Zbrodoff (1979) used a Simon task and varied the congruency proportions. When 90% of the trials were congruent, subjects showed a large congruency effect, with faster reactions on congruent compared to incongruent trials. On the other hand when 90% of the trials were incongruent, this pattern was reversed. Subjects now showed an inversed congruency effect, with faster reactions on incongruent compared to congruent trials. This seems to imply that subjects somehow kept track of the ratio of incongruent vs. congruent trials, and used this information to improve their responses. This blockwise adaptation to response conflict is also observed in other paradigms such as the Stroop task (Tzelgov et al., 1992; Merikle and Joordens, 1997), the Eriksen flanker task (Gratton et al., 1992; Purman et al., 2011), and the priming paradigm (Klapp, 2007; Jaskowski, 2008). So as with trial-by-trial adaptation, it does not seem to matter how conflict is conveyed. As long as there are regularities in a block, subjects will adapt to this manipulation by changing the impact of the irrelevant information on responding.

BLOCKWISE ADAPTATION TO UNCONSCIOUS RESPONSE CONFLICT

Based on the previous part we know that subjects strategically adapt blockwise to the frequency of conflict trials in the experiment. Are we also able to do this, when the conflicting information remains unconscious (see **Table 2** for an overview of studies addressing this issue)? Merikle and Joordens (1997) addressed this issue in an adjusted Stroop paradigm. Their subjects had to name the ink color of an array of colored ampersands. These were

Table 2 | Schematic overview of studies looking at blockwise adaptation to response conflict.

	Condition	**Prime**	**Blank**	**Backward mask**	**Target**	**Manipulation**	**Adaptation to proportion congruency**
Merikle and Joordens (1997)	Conscious	GREEN *33*	*133*	&&&&&& *133*	&&&&&&	75% incongruent	+
	Unconscious		▨	&&&&&& *267*			–
Ortells et al. (2003)	Conscious	COW *33*	*234*	&&&&&& *133*	EYE	80% incongruent	+
	Unconscious		▨	&&&&&& *367*			–
Bodner and Masson (2001)	Unconscious	Chair *60*	▨	▨	CHAIR	80 vs. 20% repetition	+
Jaskowski et al. (2003)	Unconscious	 *35*	▨	 *35*	 *35*	80 vs. 20% congruent	+

Gray boxes indicate the absence of the particular feature in a study, empty boxes indicate a blank. The numbers in the right corners indicate the duration in milliseconds.

preceded by a color word presented in gray which was incongruent in 75% of the cases with the response to the ampersands. Only in 25% of the trials the color word triggered the same response as the ampersands. Under these conditions subjects were able to strategically predict the color of the ampersands based on the color word, leading toan inversed congruency effect. The interesting observation was that subjects were only able to strategically use this conflict frequency information, when the color word was presented visibly. When this was masked, a normal Stroop effect occurred (see also Daza et al., 2002).

Similar results were presented by Ortells et al. (2003). They used a semantic priming task in which participants had to classify target words as denoting animals or body parts. In 80% of the trials the targets were preceded by a prime word of a different category (e.g., HAND–dog) and only in 20% by a semantically related prime (e.g., HAND–finger). When the primes were presented visibly, subjects were able to make use of this information leading to an inversed congruency effect. But again, if the primes were masked, subjects showed a normal congruency effect. This effect appeared to be very robust, emerging when masked and unmasked trials were randomly mixed within the same experiment (Ortells et al., 2006) and when a different task had to be performed on the targets (Daza et al., 2007).

Although these experiments highlight a qualitative difference between conscious and unconscious conditions, it cannot be assured that there was completely no blockwise adaptation to the unconscious frequency manipulation. Since these studies did not provide a baseline measure of the congruency effect, we cannot ascertain whether the congruency effect in the masked condition was, although not reversed, nevertheless diminished. Other authors, who did include a baseline condition, found blockwise adaptation to unconscious response conflict with comparable paradigms. For example, Bodner and Masson (2001) used a lexical decision task in which participants had to decide as quickly as possible whether a target string printed in uppercase (e.g., CHAIR) was a word or a nonsense letter string. Unknown to the participants the target was preceded by a 60 ms prime word in lower case. This could be a repetition of the target (e.g., chair) or an unrelated word. The authors compared groups receiving blocks where 80% of the primes were repetitions of the target and groups where only 20% of the primes were repetitions, and thus 80% of the primes were neutral. They found that participants adapted to these regularities, and the priming effect was magnified in blocks containing 80% repetition primes. This finding was repeatedly replicated and extended (see for example Bodner and Masson, 2004; Bodner and Dypvik, 2005; Bodner et al., 2006; Klapp, 2007; Bodner and Mulji, 2010).

A major problem with the previously cited studies is the prime visibility. If primes in these studies were not truly unconscious, we cannot exclude the possibility that these effects are driven by conscious influences. For example in Bodner and Masson (2001), although 77% of the subjects did not notice the primes, we cannot simply assume based on this information that their primes were truly unconscious. Additional measures need to be gathered to ensure that the results are not caused by subtle conscious influences. Unfortunately, all mentioned studies fail to satisfy this criterion. Often no objective prime awareness data is available (Bodner and Masson, 2001, 2004; Bodner et al., 2006), or subjects classify primes above chance (Klapp, 2007) and authors fail to report necessary statistics such as a significant intercept, showing priming at visibility zero (Bodner and Dypvik, 2005).

Interestingly, Jaskowski et al. (2003) showed blockwise adaptation to unconscious frequency manipulations, with a perfectly masked prime. In a priming experiment participants were presented with two target squares side by side, and had to decide as quickly as possible which of the two contained a gap. Unknown to participants, each target square was preceded by four other squares, which were shortly flashed in short succession. One or more of the first four squares also had a gap and served as primes for the target square. Each square fitted perfectly in the following, so that gaps in the prime were rendered invisible. The gaps could appear in a prime flashing before the target with a gap (i.e., congruent) or before the target without a gap (i.e., incongruent). They observed a strategic adaptation dependent on the ratio of congruent vs. incongruent trials. When 80% of the trials where congruent they observed a strong congruency effect (130 ms). When, on the contrary, only 20% of the trials were congruent they observed a reduction of the congruency effect (55 ms).

ALTERNATIVE EXPLANATIONS

Although the study of Jaskowski et al. (2003) seems to provide evidence that subjects adapted their behavior based on unconscious conflict, the authors instead explained their results by assuming a meta-cognitive process. They proposed that subjects are not aware of the conflict *per se*, but they became aware of a consequence of unconscious conflict, namely error tendencies. Because in blocks with 80% incongruent trials the prime mostly signals the erroneous response, errors are much more likely in this situation. Subjects might become aware of a higher tendency to commit errors in blocks containing mainly incongruent trials, and thereby strategically adjust their behavior to a more conservative response approach. This interpretation of their results fits nicely with the hypothesis that an unconscious stimulus itself is not able to recruit cognitive control to change on going behavior, but the conscious experience of a result of this unconscious stimulus is (Dehaene and Naccache, 2001). A similar argument was made by Van den Bussche et al. (2008). In a priming study they found a larger congruency effect for the target notation (e.g., Arabic number vs. number word) which was also presented as prime in 75% of the cases. They explained this unexpected result by suggesting that subjects may become aware of the facilitation of the target format which is also presented in 75% of the primes, without being aware of the prime or the relation between prime and target. Because of the awareness that these targets are somehow easier to respond to, subjects focus more on them, which results in stronger priming effects. These observations suggest that the effects of unconscious manipulations can be very subtle and indirect, while at first glance they seem to provide evidence for unconscious information being used to adapt subsequent behavior.

Kinoshita et al. (2008) proposed an explanation along similar lines in their Adaptation to Statistics of the Environment (ASE) model. They assume that subjects' response strategy, according to a speed accuracy dimension, is based on the difficulty of the task at hand. If an experiment contains mainly congruent primes, the task is very easy, because the prime always facilitates responding to the target. Therefore subjects can try to respond very fast without the risk of making too many errors. This will shorten reaction times to these easy targets and thus prolong reactions on the infrequent difficult (incongruent) trials. If an experiment contains mainly incongruent trials, the task at hand is now much harder. Because the prime always signals the wrong response, subjects will adopt a more cautious response deadline, in order to prevent making too many errors. If the proportion of congruent and incongruent trials is equal, a response deadline in between these two extremes will be appropriate. This will slow down responses to congruent trials and speed up responses to incongruent trials. Kinoshita et al. (2011) argued that this response deadline is mainly influenced by the difficulty of the previous trial. If the previous trial was difficult we will adopt a more cautious response strategy compared to when the previous trial was easy. Moreover, these effects are asymmetric. That is, the response to an easy trial is more sensitive to the difficulty of the previous trial than the response to a difficult trial. In their experiment 3, the authors showed that the blockwise adaptation to unconscious frequency manipulations can in fact be explained by previous trial difficulty. According to Kinoshita et al. (2011), the ASE-model can explain all studies claiming to have found blockwise adaptation to unconscious response conflict. It can be argued that the ASE-account can be seen as a more general extension of the proposal by Jaskowski et al. (2003). In the ASE-model not only the conscious error rate, but task difficulty in general can influence responses. In order for task difficulty to influence response strategies, subjects must on some level become aware of this difficulty, probably without knowing the specific origin (Van den Bussche and Reynvoet, 2008). A possible explanation for this awareness is the conscious "read out" of reaction times (Corallo et al., 2008; Marti et al., 2010). Subjects may become aware of the difficulty of the previous trial, because they consciously notice that responses on difficult (i.e., incongruent) trials are slower than on easy trials.

To summarize, the meta-cognitive accounts discussed here provide a viable alternative explanation for observed results, and point to an important methodological drawback in current research. According to the ASE-model, the most important problem when manipulating conflict frequency blockwise is that task difficulty and congruency proportion are always confounded. As a consequence, an alternative explanation can always be that subjects somehow consciously experience the task difficulty (Van den Bussche and Reynvoet, 2008) or the error tendency (Jaskowski et al., 2003). Therefore alternative ways should be addressed to investigate this question. The most important problem which has to be dealt with is the possibility that statistical regularities can somehow reach consciousness.

CONTEXT EFFECTS

A possible solution to disentangle congruency and task difficulty is to create one context with mainly congruent trials and one with mainly in congruent trials, and randomly switch between them within the same block. Thus, on each trial the probability of each context is perfectly equal. However, the probability to encounter a congruent trial is highly dependent on the context. Because every trial is randomly of either the mainly congruent or the mainly incongruent type, the various difficulties of both contexts (Kinoshita et al., 2008) cancel each other out (see **Table 3** for an overview of studies addressing this issue). Because participants need to be able to dissociate between both contexts, they need to have a way to know which of both is at hand. This is exactly what Heinemann et al. (2009) did. In a priming study, subjects had to decide whether a target digit was larger or smaller than five. Every trial started with a fixation cross, followed by a prime digit lasting 26 ms, a blank (60 ms), a mask (10 ms), and the target digit. Along with the fixation cross the authors presented a context cue in the form of a colored rectangle, whose color indicated with 80% certainty whether the upcoming trial would be congruent or incongruent. As expected, they observed that the congruency effect was larger in the context with 80% congruent trials compared to the context with 80% incongruent trials. This context-specific prime-congruency effect (i.e., CSPC) was shown before (e.g., Crump et al., 2006; Crump and Milliken, 2009), but Heinemann et al. found that it only occurred when the prime was

Table 3 | Schematic overview of studies looking at the possibility of unconscious context effects.

	Condition	Context cue	Prime	Blank	Backward mask	Target	Context effect
Heinemann et al. (2009)	Conscious	🟥->80% congruent	9 *26*	▨	%&$ *70*	1	+
	Unconscious	🟩->80% incongruent		*60*	%&$ *10*		–
Van Opstal et al. (2011)	Unconscious: high similarity	▨	A a vs. a a *33*	▨	# # *67*	4 4	+
	Unconscious: low similarity	▨	A a vs. a D *33*	▨			

Gray boxes indicate the absence of the particular feature in a study, empty boxes indicate a blank. The numbers in the right corners indicate the duration in milliseconds.

truly visible. When they filled the 60 ms blank with a mask, which rendered the prime unconscious, the congruency effect did no longer differ between the two contexts. Although the context cue was still clearly visible, its moderating effect completely vanished. Apparently, subjects in the masked condition never acquired the contingency between the cue and the congruency of the upcoming trial. A possible explanation is that an arbitrarily chosen cue is not significant enough for participants to be automatically linked to statistical regularities which remain unconscious (Van Opstal et al., 2011). To examine this possibility, future studies need to create more task-relevant, self-evident contexts, compared to presenting an arbitrary cue before every trial.

Van Opstal et al. (2011) took a first step in this direction by showing that the influence of primes on targets can be reversed by an unconscious context. In their experiment subjects had to decide whether two target digits (e.g., 4 4) were the same or different. Unknown to participants, the targets where preceded by two prime letters, which also could be equal or not. The authors compared the priming effect of moderate similar primes (e.g., a A), dependent on the context in which they were presented. Half of the subjects received these unconscious primes in a context of completely dissimilar primes (e.g., a D). In this situation these moderate similar primes were relatively equal and as a consequence facilitated "same" responses. Conversely, the other half of the subjects received these unconscious primes in a context of completely similar primes (e.g., a a). In this situation these moderate similar primes were relatively different, and as a consequence facilitated "different" responses. This nicely illustrates that an unconscious context can affect our behavior.

CONCLUSION

Summarizing research on blockwise adaptation to unconscious response conflict, the emerging picture is complicated. In an attempt to disentangle conscious and unconscious processes, some studies showed inversed congruency effects, as an adaptation to blockwise manipulation of conflict frequency, for conscious conditions only (e.g., Merikle and Joordens, 1997; Daza et al., 2002). They interpret these qualitative differences as evidence that cognitive control is exclusively reserved for consciousness. Studies showing blockwise adaptation to conflict frequency, even in unconscious conditions, challenge this conclusion (e.g., Bodner and Masson, 2001, 2004; Klapp, 2007). Nevertheless, no study to date has shown reversed congruency effects when the conflict itself remained unconscious. So a tempting conclusion would be that there are graded differences between adaptation to conscious and unconscious conflict, but adaptation can occur in both situations. Unfortunately, this conclusion is premature, since alternative meta-cognitive accounts have challenged the notion of blockwise adaptation to unconscious response conflict (e.g., Jaskowski et al., 2003; Kinoshita et al., 2008, 2011). Currently, there is just a single study to counter these criticisms (Van Opstal et al., 2011), so it would be worthwhile to test its robustness and generality in future research.

CONFLICT ADAPTATION: THE NEURAL BASIS

Behavioral studies on conflict adaptation showed a large discrepancy in the literature. Many studies find robust effects of adaptation to response conflict, when the conflict is consciously perceived. When conflict remains unconscious, the evidence is far from clear-cut. A possible tool to answer this question is to broaden the scope of research methods, and look at the neural basis of conflict adaptation. Using functional MRI (fMRI) and EEG, we can study whether certain brain areas are differentially activated by conscious and unconscious conflicting information.

CONFLICT ADAPTATION IN THE BRAIN

An interesting question is how the brain knows when to reduce the influence of conflicting information. In their conflict monitoring theory, Botvinick et al. (2001) proposed that the anterior cingulate cortex (ACC) constantly monitors for response conflict. They presume that when differential responses are suggested by stimuli, this activates the ACC which detects this response conflict. Subsequently it will in turn activate the prefrontal cortex (PFC), which then takes remedial actions to reduce this conflict. A critical discussion of this proposal lies beyond the scope of this review, so we will confine us to a clear overview of brain studies addressing response conflict. In the Stroop paradigm, there is much evidence that the ACC is indeed activated when the word meaning and the ink color trigger a different response (MacLeod and MacDonald, 2000). Also in the flanker and the Simon task, the ACC proved to be activated when there was conflict between the relevant and the irrelevant stimulus dimension (Botvinick et al., 2004; Botvinick, 2007). There is also evidence for the hypothesis that, when facing conflict, the ACC activates the PFC to cope with this conflict. In an fMRI study using the Stroop task, Kerns et al. (2004) observed that the congruency effect on the current trial was reduced, when the preceding trial was an incongruent trial which caused strong ACC activation. As expected, after incongruent trials, the dorsolateral PFC was highly activated, thus confirming its role in conflict adaptation.

Beside these effects of reactive control, other studies looked at the impact of cues which were predictive of the upcoming conflict (e.g., Sohn et al., 2007; Correa et al., 2008; Aarts and Roelofs, 2010). Sohn et al. (2007) presented input values in the form of two letters (e.g., B I) on which Boolean arithmetic tasks, according to different rules, had to be performed. All rules specified a relation between the input values (e.g., both I, one I, both not I, one not I) and an output value (e.g., I or B). Half of these rules implied low-conflict because they formed a positive relation between input and output (e.g., "if both input values are I, then the output is I"). The other half of the rules were high-conflicting because there was a negative relation between input and output (e.g., "if both input values are I, then the output is B"). Along with the input, an operator was presented which indicated which rule had to be performed on the input. On half of the trials, the authors cued the upcoming rule, by presenting the operator 9 s before the input. When no cue was presented, the ACC and lateral PFC were hardly activated. When a cue was presented, both areas were significantly more activated. Interestingly, the activation of the ACC and the lateral PFC was much higher when the cue predicted an upcoming high conflict trial, compared to an upcoming low-conflict trial. Although this seems to suggest that the ACC is not only involved in detecting response conflict, but also proactively signals that conflict is to be expected, a recent study observed no different ACC activity when comparing cues signaling upcoming congruent or incongruent trials with 75% certainty (Aarts and Roelofs, 2010). Thus, although the ACC has been shown to be activated on conflict trials, its role in anticipatory behavior is currently under debate.

Although fMRI has a good spatial resolution, its temporal resolution is very limited. To circumvent this problem, EEG can be used to look at the time course of conflict situations. In EEG studies, activation of the ACC is believed to be expressed in the N2 (Ridderinkhof et al., 2004), a negative deflection in the EEG waveform with a fronto-central scalp distribution that peaks approximately 250–350 after stimulus presentation (Yeung and Cohen, 2006). Consistent with the role of the ACC in the conflict monitoring theory, the amplitude of this component is more negative on incompatible compared to compatible trials (Wendt and Luna-Rodriguez, 2009; Clayson and Larson, 2011; Purman et al., 2011). Another component typically associated with response conflict is the P3, a positive deflection in the EEG waveform with a central–parietal distribution occurring 350–500 ms after stimulus presentation (Clayson and Larson, 2011; Frühholz et al., 2011). The latency of this component is found to be prolonged for incongruent compared to congruent trials (Purman et al., 2011). Some suggest that this is because the P3 is an index of the stimulus evaluation (Kopp et al., 1996; Purman et al., 2011), and incongruent trials take more time to be evaluated. Others have suggested that the P3 represents response inhibition (Frühholz et al., 2011), since it is more positive on incongruent compared to congruent trials (Clayson and Larson, 2011; Frühholz et al., 2011). Evidence for this latter interpretation comes from a study which points to the inferior frontal cortex, an area associated with response inhibition, as the neural generator of the P3 (Nee et al., 2007). Clayson and Larson (2011) measured both the N2 and the P3 in an Eriksen flanker task and found evidence for conflict adaptation on these components. Mirroring the sequential modulation effect in the behavioral data, the difference in amplitude between an incongruent and a congruent trial was reduced when the previous trial was incongruent, compared to congruent. This was true for both the N2 and the P3.

In summary, a large body of fMRI data confirmed the role of the ACC in detecting response conflict, and the PFC in coping with this conflict. Also EEG studies support the notion that specific brain mechanisms respond to response conflict. To get more insights into the possibility of unconscious conflict to trigger control processes, these brain measures can also be used. If unconscious conflicting information is unable to activate the ACC and the PFC, this would suggest that conflict adaptation is a preserved area for consciousness.

UNCONSCIOUS CONFLICT ADAPTATION IN THE BRAIN

In a classical brain imaging study, Dehaene et al. (1998) found that even masked primes could activate the motor cortex. In the light of this observation, it should be a fruitful approach to look whether the brain areas activated by conscious conflict, are also activated when the conflict remains unconscious. Although an overwhelming number of studies focused on the role of the ACC in conflict situations, in the area of unconscious conflict adaptation this research is very scarce. In one isolated study, Dehaene et al. (2003) replicated their previous study (Dehaene et al., 1998) and looked whether trials containing response conflict (i.e., incongruent trials) activate the ACC. As expected, when primes were visible, large congruency effects were observed and the ACC was strongly activated when comparing conflict to no-conflict trials. Interestingly, when primes were masked, no differential ACC activity was observed when comparing both trial types, despite the presence of a significant congruency effect. Thus, although the unconscious irrelevant information hampered performance, its conflict with the relevant information did not trigger the ACC. In contrast, a recent study observed activation of the caudal ACC when comparing unconscious conflict with no-conflict trials (Ursu et al., 2009). In this experiment subjects had to respond to the position of consecutively presented faces (primary task), while remembering which faces were presented (secondary task). Unknown to participants, the position of each face predicted the position of the next face with 70% accuracy. Subjects implicitly learned this rule, as evidenced by faster reaction times on predicted locations, but never became aware of this contingency because the distraction task was too demanding. On the 30% of trials where the position of the face was not predicted, the implicitly learned sequence was violated, and although subjects never consciously noticed this, the caudal ACC was nevertheless activated during this conflict.

These contradicting results seem to suggest that unconscious conflicting information can activate conflict sensitive brain regions (Ursu et al., 2009), but only when the information itself was experienced consciously (Dehaene et al., 2003). However, an alternative explanation can account for this dissociation. In the study of Dehaene et al. the congruency effect in the masked condition was, although significant, twice as small as in the visible condition. So it is possible that these authors observed ACC activation only for conscious conflict, because the conflict conveyed by the masked primes was not sufficiently strong (Mayr, 2004). Whenever conflicting information has a larger impact in the conscious condition, as evidenced by larger congruency effects, this alternative cannot be ruled out.

Other studies have looked at the potential role of the pre-SMA in dealing with unconscious conflict. In a priming study, Wolbers et al. (2006) manipulated unconscious conflict frequency blockwise. They observed a tight coupling of the pre-SMA with the lateral occipital complex and the putamen, when comparing a block with 80% incongruent trials to a block with 80% congruent trials. Likewise, in another priming study, it was shown that the size of the congruency effect was negatively correlated with the pre-SMA gray-matter density, independent of the prime visibility (van Gaal et al., 2010d). Unfortunately, prime visibility of the masked primes in both studies was far above chance-level, so it is questionable whether these results tell us something about unconscious conflict.

In summary, although a few studies addressed the brain mechanisms responsible for resolving conflict which remains unconscious, there is an important gap in the literature on this topic. So in order to learn more about the mechanisms of unconscious conflict adaptation, more brain imaging research is necessary.

GENERAL DISCUSSION

In this review we discussed studies looking at the (im)possibility of conflict which remains unconscious, to have an influence on behavior. Answering this question will help us to unravel the purpose of consciousness. Much research was stimulated by the work of Dehaene and Naccache (2001), who speculated that consciousness is a prerequisite for top-down cognitive control. Only one single study convincingly showed trial-by-trial adaptation to unconscious conflict. (van Gaal et al., 2010b). All other studies indicate that modification of behavior on a trial-by-trial basis, depending on the conflict of the previous trial, is only possible when this conflict was experienced consciously. Evidence for blockwise adaptation to conflict, is much more ambiguous. Although some studies presented qualitative differences between conscious and unconscious conditions (e.g., Merikle and Joordens, 1997), there is much evidence that subjects can adapt to unconscious statistical regularities. However, it is currently debated whether this truly reflects adaptation to unconscious conflict (e.g., Bodner and Masson, 2001, 2004) or whether it is actually an adaptation to information which somehow reached consciousness (e.g., Jaskowski et al., 2003; Van den Bussche and Reynvoet, 2008). To date, only one recent study presented evidence that unconscious stimuli can create an unconscious context, while excluding meta-cognitive explanations (Van Opstal et al., 2011). An alternative to circumvent problems of behavioral studies is to look at brain measures of unconscious conflict. Unfortunately, although a large body of research explored the brain mechanisms involved in conscious conflict (Botvinick et al., 2004), this type of research is virtually lacking in the field of unconscious conflict adaptation.

In the remainder of this review we will discuss the conclusiveness of existing studies regarding these questions. We will look at strengths and weaknesses of all studies and give some suggestions how future research can tackle questions which research hitherto failed to answer conclusively.

ARE WE LOOKING AT COGNITIVE CONTROL?

An important point in the research on unconscious conflict adaptation is that we should be cautious about the origin of an effect. We should not be satisfied showing that a result can also be obtained when the conflicting information is masked, but also take into account the uncertainties this area faces. Namely, we should be sure that the behavior under investigation is an expression of cognitive control at all. For both issues discussed here, trial-by-trial and blockwise adaptation to response conflict, alternative explanations in terms of low-level learning have been proposed (Logan, 1988; Hommel, 1998). Hommel (1998) claimed that trial-by-trial adaptations could be perfectly explained without assuming any control process. He argued that trials are responded to fastest when the stimulus and response features are exact repetitions or complete alternations from these features on the previous trial. If only some features, but not all, overlap with the previous trial, this will create interference and slow down responses. This low-level learning mechanism can completely explain sequential modulations, without assuming cognitive control processes (e.g., Mayr et al., 2003; Hommel et al., 2004; Nieuwenhuis et al., 2006; Mayr and Awh, 2009). Likewise, blockwise adaptation to response conflict can also be explained by low-level learning mechanisms. When 80% of the trials are congruent, we have also practiced these trial types more often. It is well known that we become faster with more practice (Logan, 1988), so the effect can be perfectly explained, without assuming any influence of top-down cognitive control. It can even be argued that blockwise adaptation to response conflict is actually an expression of trial-by-trial adaptation (e.g., Kinoshita et al., 2011). If a block consists of 80% incongruent trials, the previous trial will be by definition incongruent on 80% of the trials. The cognitive system will react to this by reducing the influence of the irrelevant information (Gratton et al., 1992), which will reduce the congruency effect on 80% of the current trials. On average this will cause small congruency effects, which can be misleadingly taken as evidence for blockwise adaptation to conflict. Although there is compelling evidence that trial-by-trial adaptations (e.g., Ullsperger et al., 2005; Kunde and Wühr, 2006; Notebaert and Verguts, 2007), and blockwise adaptation (Tzelgov et al., 1992) cannot entirely be explained by these accounts, studies who try to show that these effects can also occur when conflict remains unconscious, should take these explanations into consideration and try to rule them out. For example, when manipulating conflict frequency blockwise, with only a limited number of stimuli (e.g., Klapp, 2007) reaction times are always confounded with the frequency with which certain prime-target combinations (i.e., congruent or incongruent) are exposed. To rule out this low-level learning mechanism, the stimulus set can be enlarged, so that all primes and targets occur equally often (Bodner and Masson, 2001; Egner and Hirsch, 2005; Crump and Milliken, 2009). Likewise, as long as two consecutive trials with the same congruency are complete repetitions or complete alternations, and two consecutive trials with a different congruency always partial repetitions, a feature explanation can always explain trial-by-trial adaptations. To rule out this explanation, more than two response options (Kunde and Wühr, 2006; Lamers and Roelofs, 2011) or more than two stimulus dimensions (Kunde and Wühr, 2006) can be used, so that all consecutive trials are complete alternations.

ARE WE COMPARING CONDITIONS BASED ON A DIFFERENCE IN CONSCIOUSNESS?

To provide conclusive evidence that adaptation to response conflict cannot be initiated by unconscious stimuli, we have to ascertain that the only difference between the conscious and the unconscious condition is solely consciousness. In the conscious condition subjects need to be aware of the conflict and in the unconscious condition they must not be aware of the conflict, not on any level (e.g., Jaskowski et al., 2003; Van den Bussche et al., 2008). Although this seems a trivial requirement, existing paradigms do not seem to be able to satisfy this criterion. For example, Kunde (2003) and van Gaal et al. (2010b) varied the SOA to create a conscious and an unconscious condition. Frings and Wentura (2008) matched the SOA between both conditions, but failed to keep the prime duration constant. Even when prime duration and SOA are perfectly matched between both conditions (e.g., Ansorge et al., 2011), the absence of unconscious sequential modulations can still be explained by other accounts. Primes are typically followed by a maskin the unconscious condition and by a blank in the conscious condition. Because this mask rapidly destroys the presented image, this also impedes prime processing in this condition. As a consequence, the signal strength of the prime is much stronger in the unmasked condition (Lau, 2009; Francken et al., 2011), and these primes had more possibility to activate conflict sensitive regions (Dehaene et al., 2003), and influence behavior on the subsequent trial. This difference in signal strength is typically expressed in significantly smaller (e.g., Greenwald et al., 1996; Dehaene et al., 2003; Kunde, 2003; van Gaal et al., 2010b), or at least numerically smaller (e.g., Frings and Wentura, 2008; Ansorge et al., 2011) congruency effects in the unconscious condition. To deal with this problem, Francken et al. (2011) proposed to match for these low-level differences in signal strength by masking all primes equally long. To create conscious and unconscious conditions they used effective (i.e., meta-contrast masking for low-visible trials) and ineffective (i.e., pseudomasking for high-visible trials) masks. They observed identical priming effects in both conditions. However, although the authors showed that the priming effect for high and low visible primes is identical when the signal strength is matched, the question remains whether this is also the case with a truly unconscious condition. Nevertheless, this is an important first step, because only if also the signal strength is matched between both conditions, more firm conclusions can be drawn about unconscious trial-by-trial adaptation.

ARE UNCONSCIOUS PRIMES UNQUESTIONABLY UNCONSCIOUS?

As a final remark we want to discuss measures of prime visibility. If we want to be sure a prime was truly unconscious, we have to provide strong evidence to support this. Again, although this seems a trivial requirement, many studies fail to satisfy this point. This ranges from no detection task at all (Merikle and Joordens, 1997; Bodner and Masson, 2001, 2004; Ortells et al., 2006), up to the absence of adequate follow-up analyzes when the detection task is above chance-level (Ortells et al., 2003; Bodner and Dypvik, 2005; Klapp, 2007). Additional analyses showing no correlation between our detection measure and our priming effect, a significant intercept showing priming at zero visibility, or the presence of the effect in a subgroup with zero visibility, can give us more confidence about the unconscious nature of the primes. Although the introduction of post detection tasks was a major progress in research on subliminal processing (Kouider and Dehaene, 2007), this measure does not suffice in research on unconscious conflict adaptation. This is because unconscious sequential modulations can be caused by trial-by-trial adaptations to the *difficulty* of the previous trial rather than to the *conflict*. Likewise, blockwise adaptation to unconscious conflict can be caused by adaptation to the conscious difficulty of a block. Therefore it is necessary to collect prime awareness data on every trial, to control for these possibilities. A disadvantage of this measure is that these long inter-trial interruptions possibly wipe out short-lived unconscious traces, which will impede trial-by-trial adaptation. Nevertheless, without this information we cannot dissociate between truly unconscious adaptation, and adaptation to information which somehow reached consciousness (Jaskowski et al., 2003; Van den Bussche et al., 2008).

CONCLUSION

In this review we gave a clear overview of research looking at the possibility of unconscious information to trigger adaptation behavior. Dehaene and Naccache (2001) speculated that top-down cognitive control is one class of behavior which can only be initiated consciously. Although there is some evidence that adaptation to unconscious conflict both on a trial-by-trial and blockwise basis is possible, almost all evidence suffers from serious methodological and theoretical problems, which hampers progression in this important field of research. In future research, it should be further clarified to which extent unconscious stimuli are able to trigger conflict adaptation, while avoiding the problems discussed in this review. This will help us to further elucidate the purpose of consciousness.

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Executive control over unconscious cognition: attentional sensitization of unconscious information processing

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Unconscious priming is a prototypical example of an automatic process, which is initiated without deliberate intention. Classical theories of automaticity assume that such unconscious automatic processes occur in a purely bottom-up driven fashion independent of executive control mechanisms. In contrast to these classical theories, our attentional sensitization model of unconscious information processing proposes that unconscious processing is susceptible to executive control and is only elicited if the cognitive system is configured accordingly. It is assumed that unconscious processing depends on attentional amplification of task-congruent processing pathways as a function of task sets. This article provides an overview of the latest research on executive control influences on unconscious information processing. I introduce refined theories of automaticity with a particular focus on the attentional sensitization model of unconscious cognition which is specifically developed to account for various attentional influences on different types of unconscious information processing. In support of the attentional sensitization model, empirical evidence is reviewed demonstrating executive control influences on unconscious cognition in the domains of visuo-motor and semantic processing: subliminal priming depends on attentional resources, is susceptible to stimulus expectations and is influenced by action intentions and task sets. This suggests that even unconscious processing is flexible and context-dependent as a function of higher-level executive control settings. I discuss that the assumption of attentional sensitization of unconscious information processing can accommodate conflicting findings regarding the automaticity of processes in many areas of cognition and emotion. This theoretical view has the potential to stimulate future research on executive control of unconscious processing in healthy and clinical populations.

Keywords: unconscious information processing, automatic processes, attentional control, visuo-motor priming, semantic priming, emotional priming, subliminal perception

INTRODUCTION

Unconscious processes are prototypical examples of automatic processes, which are initiated without deliberate intention (Posner and Snyder, 1975). An important method to measure unconscious processes are subliminal priming (e.g., facilitatory) effects on subsequent decisions or actions on visible targets, which are elicited by masked visual stimuli that are not consciously perceived (Greenwald et al., 1996; Vorberg et al., 2003; Kiefer, 2007). Typically, a pattern or metacontrast mask is presented after—or in the case of pattern masking also before the prime—to prevent its conscious perception (Breitmeyer and Öğmen, 2006). Although these stimuli cannot be consciously perceived, there are meanwhile numerous demonstrations that they trigger cognitive processes at several levels of complexity and thus can influence decisions and actions (for reviews see, Dehaene et al., 2006; Kiefer et al., 2011; Schmidt et al., 2011; Ansorge et al., 2011b; Kunde et al., 2012).

According to classical theories of cognitive control and automaticity (Posner and Snyder, 1975; Schneider and Shiffrin, 1977), such unconscious processes are automatic in the sense that they occur in a purely bottom-up driven fashion independent of attentional control mechanisms. Attentional executive control mechanisms that organize action and thought (Norman and Shallice, 1986; Posner and DiGirolamo, 1998) according to higher-level goals are assumed to be exclusive to the domain of conscious cognition. Classical theories of cognitive control, therefore, propose that only conscious processes depend on capacity-limited attentional resources and can be modulated by executive control. This alleged association of executive control and attention with the domain of conscious cognition has been recently challenged in two respects: (1) Unconscious stimuli influence executive control settings. Several experiments showed that subliminal stimuli can modulate shifts of spatial (Ansorge et al., 2002; Scharlau and Ansorge, 2003) and modality-specific attention (Mattler, 2003, 2005) as well as task-specific control operations (Mattler, 2003, 2005, 2006) and task sets (Reuss et al., 2011; Wokke et al., 2011). (2) Furthermore, the relation between executive control and unconscious processing is bidirectional because top-down factors such as attentional resources, stimulus expectations, action intensions, or task sets, all factors that are typically considered to involve executive control mechanisms (Norman and Shallice, 1986), modulate unconscious stimulus processing (Jaśkowski et al., 2003; Ansorge and Neumann, 2005; Kiefer and Martens, 2010; Wokke et al., 2011). Hence, these two lines of research suggest that executive control mechanisms interact with unconscious information processing in several ways and are thus not exclusive to the domain of conscious cognition (Kiefer et al., 2011).

This article provides an overview of the latest research on executive control influences on unconscious information processing. I introduce refined theories of automaticity with a particular focus on the attentional sensitization model of unconscious cognition (Kiefer and Martens, 2010) which is specifically developed to account for various executive control influences on different types of unconscious information processing. In support of these refined theories of automaticity, empirical evidence is presented demonstrating attentional influences on unconscious cognition in the domains of visuo-motor and semantic processing. This suggests that even unconscious processing is flexible and context-dependent as a function of executive control settings.

CLASSICAL VERSUS REFINED THEORIES OF AUTOMATICITY

The classical view of executive control and automaticity is still influential and pervades current theorizing about automaticity and cognitive control. The core assumption of this view that executive control is exclusive to the domain of conscious cognition while unconscious automatic processes are autonomous (Posner and Snyder, 1975; Schneider and Shiffrin, 1977) implies that a behavioral or neurophysiological effect has to be context-independent in order to index a "truly automatic" process (Pessoa et al., 2003). Such operational definitions of automaticity, which are essentially influenced by the classical view, can be found in many areas of psychology and neuroscience such as object or face recognition (e.g., Pessoa et al., 2002; e.g., Wiese et al., 2008), action preparation (e.g., Bub and Masson, 2010), and emotional processing (e.g., Pessoa et al., 2002). However, it is difficult to identify processes that actually meet the classical criteria for automaticity because task demands frequently modulate behavioral and neurophysiological effects (see also, Moors and De Houwer, 2006). As almost all kind of cognitive activity has to be classified as "controlled" according to classical criteria, the distinction between strategic and automatic processing becomes practically superfluous. This renders the classical view of automaticity unsatisfactory. Furthermore, if unconscious automatic processing were context-independent, this would result in a tremendous inflexibility of the cognitive system (Kiefer and Martens, 2010): conscious goal-directed information processing would be massively influenced by various unconscious processes. Demands on conscious executive control would be increased, because the intended action could only be ensured by inhibiting numerous interfering response tendencies induced by unconscious information processing (Botvinick et al., 2001).

Refined theories of automaticity and unconscious processing allow for more flexibility and adaptability of unconscious automatic processing (Neumann, 1990; Naccache et al., 2002; Moors and De Houwer, 2006; Kiefer, 2007; Kiefer and Martens, 2010). These theories posit that unconscious or automatic processing in general depends on a configuration of the cognitive system by attention and task sets. Neumann (1990) proposes in his theory of direct parameter specification (DPS) that unconscious information will only be processed and will influence the motor response to a target stimulus to the extent that it matches current intentions. Similarly, the global workspace model of consciousness by Dehaene and Naccache (2001) explicitly assumes that unconscious processes are susceptible to attentional amplification. Unlike classical theories, refined theories propose that executive control factors such as attention, intentions, and task sets orchestrate the unconscious processing streams toward greater optimization of task performance. Given this dependency on the precise configuration of the cognitive system, the term "conditional automaticity" has been coined (Bargh, 1989; Logan, 1989).

THE ATTENTIONAL SENSITIZATION MODEL OF UNCONSCIOUS COGNITION

Although previous refined theories of automaticity agree that automatic processes are susceptible to top-down control, they do not account for a number of executive control factors and different forms of automatic processes. The attentional sensitization model of unconscious cognition (Kiefer and Martens, 2010) was developed within this line of research, but aims at explaining the various influences of executive control factors on different forms of unconscious automatic processing. It is proposed that attentional influences originating from task sets enhance task-relevant unconscious processes while attenuating task-irrelevant unconscious processes. Task sets are defined as an adaptive configuration of the cognitive system which is necessary to efficiently perform a given task (Rogers and Monsell, 1995; Kiesel et al., 2010). The concept of "task set" refers to the immediate computational consequences of pursuing a current goal during task performance that are implemented by executive control mechanisms (Kiesel et al., 2010).

Much as conscious perception is influenced by attentional mechanisms, unconscious cognition is thought to be controlled by top-down signals from prefrontal cortex (Haynes et al., 2007) that increase or decrease the sensitivity of processing pathways for incoming sensory input (Hopfinger et al., 2000, 2001; Bode and Haynes, 2008). Processing in task-relevant pathways is enhanced by increasing the gain of the neurons in the corresponding areas, whereas processing in task-irrelevant pathways is attenuated by a decrease of the gain (Reynolds et al., 2000). Gain is a parameter in neural network modeling, which influences the probability that a neuron fires at a given activation level (Hamker, 2005). Single cell recordings in non-human primates have shown that the likelihood of a neuron firing, given a constant sensory input, is enhanced when the stimulus dimension that is preferentially processed by the neuron is attended to (e.g., Treue and Martínez Trujillo, 1999). Hence, the attentional sensitizing mechanism is thought to gradually enhance and attenuate stimulus processing irrespective of whether the stimulus is consciously perceived or not (Kiefer and Martens, 2010).

Two basic predictions can be derived from the attentional sensitization model: in a manner similar to conscious strategic processes, unconscious automatic processes (1) should depend on available attentional resources, and (2) should be susceptible to executive control by currently active task representations. Attentional sensitization of unconscious processing by task representations is achieved by enhancing the sensitivity of task-relevant pathways and by attenuating the sensitivity of task-irrelevant pathways.

Although executive control of both unconscious and conscious processing shares basic computational principles, control of conscious strategic processing is more flexible in several respects. Preemptive control, in which top-down influences are initiated in advance of stimulus presentation, can be exerted for both conscious and unconscious stimulus presentation, whereas only consciously perceived stimuli are susceptible to reactive control in response to ongoing or completed stimulus processing (Ansorge and Horstmann, 2007; Kiefer, 2007; Ansorge et al., 2009, 2011a; Kiefer and Martens, 2010). For that reason, subliminal information cannot be used for determining further strategic processing steps in a deliberate or intentional fashion (Merikle et al., 1995). Executive control of unconscious information processing cannot be exerted intentionally in anticipation or response to subliminal stimuli themselves because individuals are not aware of them by definition. Executive control in the unconscious domain must occur indirectly on the grounds of other representations, whether conscious or unconscious: executive control can be based on a currently active conscious action goal that is internally generated by the individual or externally induced by task instructions (Ansorge and Neumann, 2005). Executive control can also be based on the consciously perceived outcome of overt behavior, which leads to an adjustment of control settings (Jaśkowski et al., 2003). These conscious goal or outcome representations establish or modify task sets that in turn regulate the sensitivity of processing pathways for both conscious and unconscious information. As mentioned at the beginning of this article, control settings are not only intentionally created in a conscious mode, but can also be unconsciously triggered by subliminal stimuli such as attentional or task cues (e.g., Ansorge et al., 2002; Mattler, 2005; Reuss et al., 2011). However, as executive control in the unconscious domain is preemptive, subliminal stimuli that trigger or modify cognitive control settings must be presented before the unconscious process of interest is elicited (e.g., by a subliminal prime). According to the attentional sensitization model, intentional application of control and on-line modification is restricted to conscious strategic processes (see also Dehaene et al., 2006). Finally, executive control of unconscious processing is presumably based on facilitatory influences, that is, it depends on differential attentional sensitization, whereas active inhibition of task-irrelevant information appears to be confined to controlled processing of consciously perceived stimuli (Posner and Snyder, 1975; Neely, 1977; Merikle et al., 1995). Thus, according to the attentional sensitization model conscious stimulus processing, which is traditionally considered to be "strategic," allows for a greater adaptability and flexibility of executive control than unconscious automatic information processing (for a discussion see, Kiefer and Martens, 2010). One can, therefore, distinguish even within the light of refined theories of automaticity strategic and automatic processes although the defining criteria differ from classical theories in several aspects.

EXECUTIVE CONTROL INFLUENCES ON UNCONSCIOUS INFORMATION PROCESSING

In the upcoming parts of this article, I will review latest evidence demonstrating executive control influences on unconscious visuo-motor and semantic information processing in support of the attentional sensitization model of unconscious cognition.

UNCONSCIOUS VISUO-MOTOR PROCESSING

Unconscious visuo-motor processing is typically investigated with the masked visuo-motor response priming paradigm (subliminal visuo-motor priming): responses to visual targets are faster, when the masked prime (also a visual stimulus) indicates the same (congruent) rather than a different (incongruent) response (Neumann and Klotz, 1994; Dehaene et al., 1998; Vorberg et al., 2003; Ansorge and Neumann, 2005). In this paradigm, a visual shape is frequently arbitrarily assigned with a motor response (Schmidt et al., 2011). This form of priming depends on visuo-motor processes that give rise to response conflict in the incongruent condition. In line with this interpretation, visuo-motor response priming modulates ERPs over the occipito-parietal scalp in a time window between 200 and 400 ms (Jaśkowski et al., 2003; Martens et al., 2011). These ERPs most likely arise from the parietal visuo-motor system as identified in a previous functional magnetic resonance imaging (fMRI) study (Wolbers et al., 2006).

In line with the proposed notion of executive control over unconscious processing, subliminal visuo-motor priming effects were shown to be influenced by action intentions and stimulus expectations. The influence of action intentions has been intensively studies by Ansorge and colleagues (e.g., Ansorge et al., 2002, 2010; Ansorge and Neumann, 2005). They found that unconsciously perceived masked primes trigger responses only if they are congruent with the current intentions of a person. Visuo-motor priming effects were abolished when task instructions were changed in such a way that primes ceased to be task-relevant. For instance, primes and targets with a similar shape elicited subliminal response priming effects only when the response decision was based on the target's shape (Ansorge and Neumann, 2005). However, when the instruction of the target task was changed such that the response decision was based on the target's color, response priming effects disappeared although primes and targets still exhibited similar or dissimilar shapes (Ansorge and Neumann, 2005). In a comparable experiment, shape or color congruency of masked primes and visible targets only primed target responses, when the corresponding prime feature (e.g., shape feature during shape decisions on the target) was relevant in the target task (Tapia et al., 2010). The task-irrelevant prime feature did not influence responses to targets (see also, Wokke et al., 2011). Similarly, spatial congruency of prime and target words indicating either an elevated (e.g., "above") or a lowered location (e.g., "below") produced priming effects only during a spatial target task, but not during a target task with numbers of high and low numerical magnitude (Ansorge et al., 2010). These findings suggest that action intentions sensitize congruent and desensitize incongruent unconscious processing pathways: it is proposed that an attentional top-down signal enhances unconscious processing of the stimulus dimension that matches the current intention

(Kiefer and Martens, 2010). Attentional sensitization results in subliminal priming effects on responses to visible targets only for stimulus dimensions that are congruent with the current action intention.

In addition to action intentions, unconscious visuo-motor processing has been shown to depend on stimulus expectations. Stimulus expectations establish an attentional set, which indicates what kind of stimuli are likely to occur within a given situation. Expected subliminal stimuli receive attentional amplification and are more efficiently processed whereas processing of unexpected stimuli is attenuated. It should be noted that expectations cannot be established by unconsciously presented stimuli themselves, but must be formed by consciously perceived stimuli presented within a given context, for instance by the visible target stimuli of a priming paradigm. It has been shown that the type of visible target stimuli included in an experiment strongly influences subliminal priming effects: masked stimuli prime responses only if they are expected and represent possible release conditions for prepared actions to the visible targets (Kunde et al., 2003; Eckstein and Perrig, 2007; Kiesel et al., 2009). Subliminal visuo-motor priming effects elicited by novel primes, which are not presented as targets, are only obtained when they belong to or are at least similar to the attentional set established by the visible targets: for instance, subliminally presented novel numbers prime numerical categorizations of visible numbers only when they are located within the magnitude space spanned by the visible targets (e.g., the prime numbers “2” and “3” are within the magnitude space spanned by the visible targets “1” and “4”), but not when they are outside the magnitude space spanned by the visible targets (e.g., the prime numbers “1” and “2” are outside the magnitude space spanned by the visible targets “3” and “4”). Expectancy effects on unconscious visuo-motor priming were also obtained for novel verbal stimuli within a semantic categorization task when the target set size was manipulated (Kiesel et al., 2006). When target set size was large (40 targets) so that a variety of words from different semantic categories was expected, novel word primes elicited visuo-motor priming effects. However, when target set size was small (four targets) so that attention could be focused on a narrow set of stimuli, novel word primes did not produce subliminal priming. These findings demonstrate that stimulus expectations establish an attentional set that sensitizes the corresponding visuo-motor processing pathways for unconscious stimuli. As a result, only expected subliminal stimuli elicit priming effects.

Unconscious visuo-motor processing does not only depend on specific stimulus expectations, but is also influenced by focusing attention in time: subliminal visuo-motor priming in a numerical judgment task was only obtained when the onset of the prime-target pairs was temporally predictable and therefore, attended to (Naccache et al., 2002). Hence, not only the content of the attentional set (specific stimulus expectations), but also the temporal dynamics of attention plays an important role in executive control of unconscious visuo-motor processes.

The mechanisms underlying attentional influences on unconscious visuo-motor processing were further specified in a study using the induction task paradigm (Martens et al., 2011). The induction task paradigm was recently developed (Kiefer and Martens, 2010) to specifically test the predictions of the attentional sensitization model (see **Figure 1A**). It allows directly investigating the influence of activated task sets on unconscious information processing, irrespective of action intentions to visible targets or global stimulus expectations. In this paradigm, two different tasks are performed in quick succession: the subliminal priming task is preceded by different classification tasks serving to activate specific task sets. As task sets are active for about 600 ms after task completion (Rogers and Monsell, 1995), they should influence processing of subsequently presented subliminal primes.

In our study (Martens et al., 2011), the subliminal visuo-motor priming task required participants to perform right or left-hand responses to discriminate between geometrical target shapes (e.g., circle or square). The visible target was preceded by a masked prime that either indicated the same or a different motor response, but was never combined with the identical shape to avoid repetition effects. Prior to this subliminal visuo-motor priming task, participants were engaged in a perceptual classification (round vs. elongated object) or in a semantic classification task (living vs. non-living object) designed to induce a specific task set (e.g., a perceptual or semantic task set). These induction tasks were followed immediately by the priming task. According to the proposed attentional sensitization model, visuo-motor priming should benefit from a previous sensitization of visual pathways by the perceptual induction task compared with the semantic induction task. In line with these predictions, behavioral and electrophysiological effects showed a differential modulation of subliminal visuo-motor priming by the induction tasks: visuo-motor priming, depending on access to visual shape information, was only observed after the perceptual but not after the semantic induction task (see **Figure 1B**).

In a continuation of this line of research, the induction task paradigm was used for a fine-grained analysis of task set influences on unconscious visuo-motor response priming. There is evidence that shape and color of visible objects can be attended to and processed independently of each other (Boucart et al., 1995). Based on these findings, the induction task was varied within the perceptual domain to further assess whether the proposed attentional sensitization mechanism not only distinguishes between broad cognitive domains such as visual vs. semantic stimulus attributes but also specifically sensitizes stimulus attributes within the perceptual domain (Zovko and Kiefer, submitted). The effects of a shape decision induction task similar to previous experiments (Kiefer and Martens, 2010) was contrasted with a novel color decision task, in which the hue of colored object picture had to be classified (red vs. blue). In the visuo-motor priming task, participants performed again right or left-hand responses to discriminate between geometrical target shapes (Martens et al., 2011). Occipito-parietal ERP priming effects were only found subsequent to the shape induction task. No such effects were found subsequently to the color induction task. These results show that attentional influences can also occur within perceptual subdomains, such as shape and color attributes. Attentional sensitization thus modulates unconscious visuo-motor processes fine-grained at the level of specific visual object features.

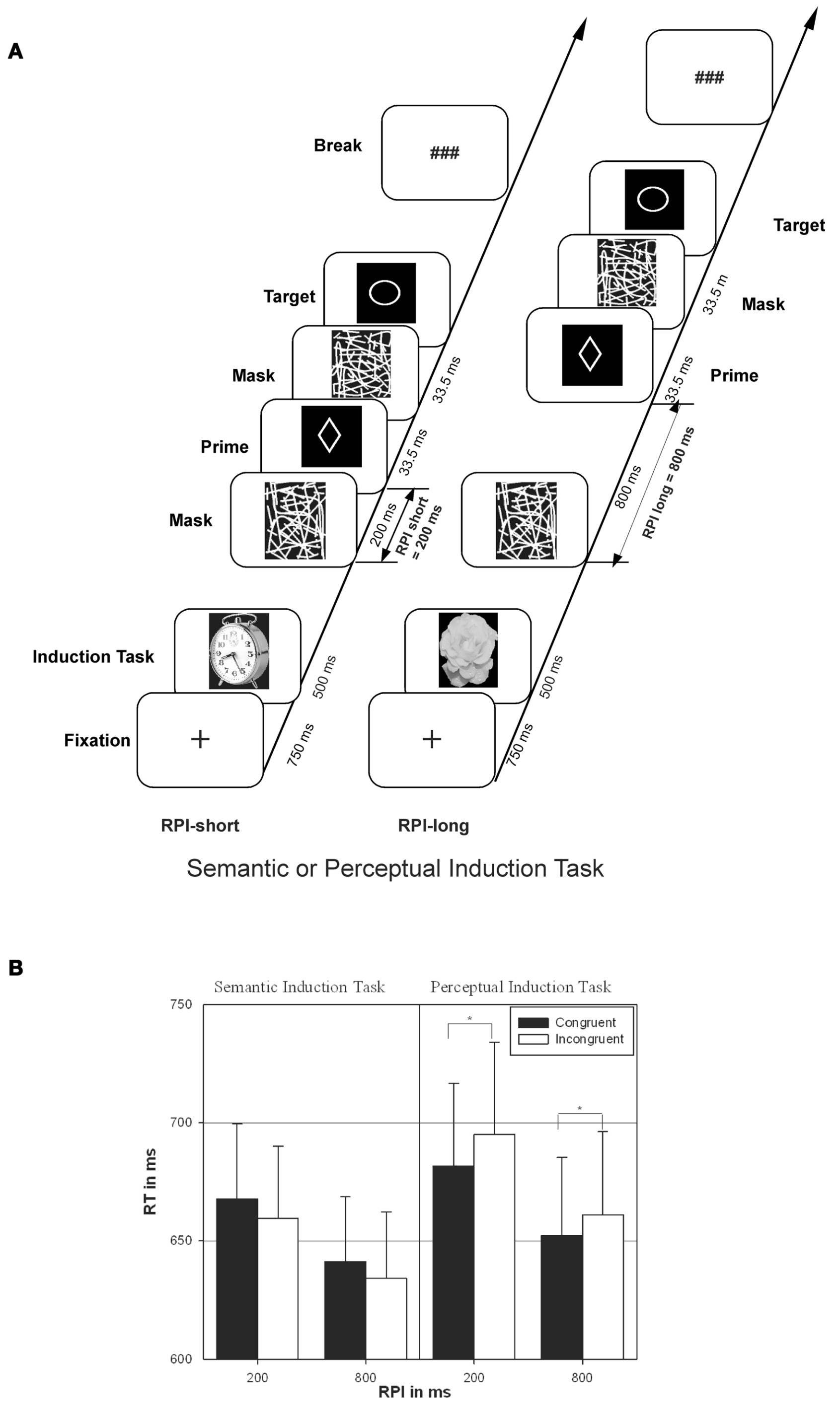

FIGURE 1 | (A) Induction task paradigm in combination with a masked visuo-motor priming task. The masked prime shape was presented either 200 ms or 800 ms following the response to the induction task (response prime interval, RPI) that is intended to elicit the corresponding task set. The RPI was varied in order to capture the temporal dynamics of task set activation. The semantic induction task required semantic classification (forced choice living/non-living decision) of the inducing picture, whereas the perceptual induction task required a forced choice perceptual classification decision of the pictured object (round/elongated shape). Subsequent to masked prime presentation, the target shape was presented, which required a right- or left-hand response. In the congruent priming condition, prime and target shape afforded the same manual response whereas in the incongruent condition, prime and target were associated with different response hands. **(B)** Behavioral unconscious visuo-motor priming effects of Exp. 2 of the Martens et al. (2011) study. Mean correct response times and their standard error in the target shape discrimination task, as a function of response congruency, induction task, and RPI. The asterisks indicate significant masked priming effects (difference between incongruent and congruent prime-target responses) within each induction task/RPI combination. Significant unconscious visuo-motor priming effects were only obtained following the perceptual induction task, but not following the semantic induction task. Modified after Kiefer and Martens (2010) and after Martens et al. (2011).

UNCONSCIOUS SEMANTIC PROCESSING

Semantic processing of conceptual information provides the basis for thought, problem solving and action planning (for recent overviews see, Kiefer and Pulvermüller, 2011; Kiefer and Barsalou, 2012) and is also crucial for language and communication because it constitutes word meaning (Levelt et al., 1999). Semantic processing is, therefore, typically characterized as a higher-level cognitive process compared with more lower-level perceptually based visuo-motor processes (Engelkamp and Zimmer, 1994; Anderson, 2000). Nevertheless, there are meanwhile numerous demonstrations that semantic meaning is also processed unconsciously (e.g., Marcel, 1983; Carr and Dagenbach, 1990; Draine and Greenwald, 1998; Dell' Acqua and Grainger, 1999; Kiefer and Spitzer, 2000; Rolke et al., 2001; Kiefer, 2002; e.g., Kiefer and Brendel, 2006). Unconscious semantic processing can be demonstrated with the masked semantic priming paradigm. Semantic priming generally refers to a facilitation of a response to a meaningful target (e.g., word or picture), when it is preceded by a semantically related masked prime (Neely, 1977, 1991). For instance, lexical (word/pseudoword) decisions on word targets are faster, when they are preceded by a semantically related prime word (e.g., "chair-table") compared with unrelated pairings (e.g., "car-hen"). In contrast to visuo-motor priming, primes in the semantically related and unrelated conditions always afford the same response in the target task (word response in the lexical decision task) thereby ruling out any response congruency effects. In masked semantic priming, a pattern mask prevents conscious identification of the prime word. Nevertheless, responses to targets that have been preceded by a semantically related prime are performed more quickly than responses to targets paired with unrelated primes demonstrating unconscious access to word meaning (Carr and Dagenbach, 1990; Kiefer and Spitzer, 2000; Kiefer, 2002; Kiefer and Brendel, 2006). Neuroimaging (Mummery et al., 1999) and electrophysiological studies (Nobre and McCarthy, 1995; Kiefer et al., 2007) show that semantic priming depends on anterior temporal areas (ventral pathways) supporting semantic integration (Kiefer and Pulvermüller, 2011). Semantic priming modulates the N400 ERP component, a negative deflection peaking at about 400 ms with centro-parietal topography (Kutas and Hillyard, 1980). The N400 semantic priming effect is reflected by an attenuated N400 amplitude (i.e., relatively less negative voltage) to a target when preceded by a semantically related as compared with an unrelated prime (Bentin et al., 1985; Kiefer et al., 1998). Intracranial ERP recordings (Nobre and McCarthy, 1995) and source analyses of scalp potentials (Kiefer et al., 2007) have implicated a region in the anterior-ventral temporal lobe in generating the N400 ERP component.

There is meanwhile accumulating evidence that similar to visuo-motor priming unconscious semantic priming is modulated by executive control factors (for a recent review, see Kiefer et al., 2012). In fact most of the empirical tests of the attentional sensitization model of unconscious cognition with the induction task paradigm described above have been conducted within the field of unconscious semantic processing.

Similar to conscious semantic priming (for a review see, Deacon and Shelley-Tremblay, 2000), unconscious semantic priming has been shown to depend on attentional resources: in a masked semantic priming study within a lexical decision task (word/non-word decision) (Kiefer and Brendel, 2006), an attentional cue prompted participants to attend to the stimulation stream either during the time window of masked prime presentation or already one second earlier. In the latter long cue prime interval condition, subjects already had disengaged attention when the masked prime was finally presented. Kiefer and Brendel (2006) obtained a subliminal semantic priming effect on the N400 ERP component, but only when the masked prime was presented within the time window of attention. Hence, comparable to the findings in visuo-motor priming (Naccache et al., 2002), subliminal semantic priming depends on temporal attention. Furthermore, masked semantic priming was significantly reduced when the masked prime was preceded by a difficult primary task requiring greater attentional resources compared with an attentionally undemanding task (Martens and Kiefer, 2009). These influences of attentional capacity on unconscious semantic processing are in line with our proposal (Kiefer and Martens, 2010) that attention and conscious experience are functionally independent to some extent and should not be equated (see also, Koch and Tsuchiya, 2007; see also, Van Boxtel et al., 2010).

Using the induction task paradigm already described above, we systematically investigated the influence of activated task sets on subsequent masked semantic priming (Kiefer and Martens, 2010; Martens et al., 2011). It was assessed whether a semantic task set induced by a semantic decision task (e.g., living/non-living decision) immediately before masked prime presentation sensitizes semantic processing pathways and enhances subliminal semantic priming (see **Figure 2A**). In contrast, a perceptual task set induced by a task that requires attention to visual stimulus features (letter or object shape decision) should desensitize semantic pathways and therefore, attenuate subsequent subliminal semantic priming. The time interval between the response to the induction task and the onset of the prime (RPI) (either 200 or 800 ms) was varied in order to obtain information on how the influence of the induction task on masked priming unfolds over time. We expected that a semantic induction task sensitizes semantic processing pathways and thus enhances semantic priming only at the short RPI (200 ms) because the task switching literature suggests that a task representation is active for about 600 ms after task completion (Rogers and Monsell, 1995), but is actively inhibited thereafter (Mayr and Keele, 2000).

Across experiments, the difficulty of the semantic and perceptual induction tasks as well as their verbal or non-verbal nature was systematically varied. For instance, in one experiment (Kiefer and Martens, 2010), participants performed an easy semantic word classification task (living/non-living decision) and a difficult perceptual letter classification task with words (first or last letter of a word has a closed or open shape). In other experiments (Kiefer and Martens, 2010; Martens et al., 2011), non-verbal induction tasks, which exhibited the same level of difficulty, required semantic classification (living/non-living decision) vs. perceptual classification (round vs. elongated shape decision) of object pictures (see **Figure 2A**).

Comparable results were obtained regardless of the difficulty level and the verbal or non-verbal nature of the induction tasks

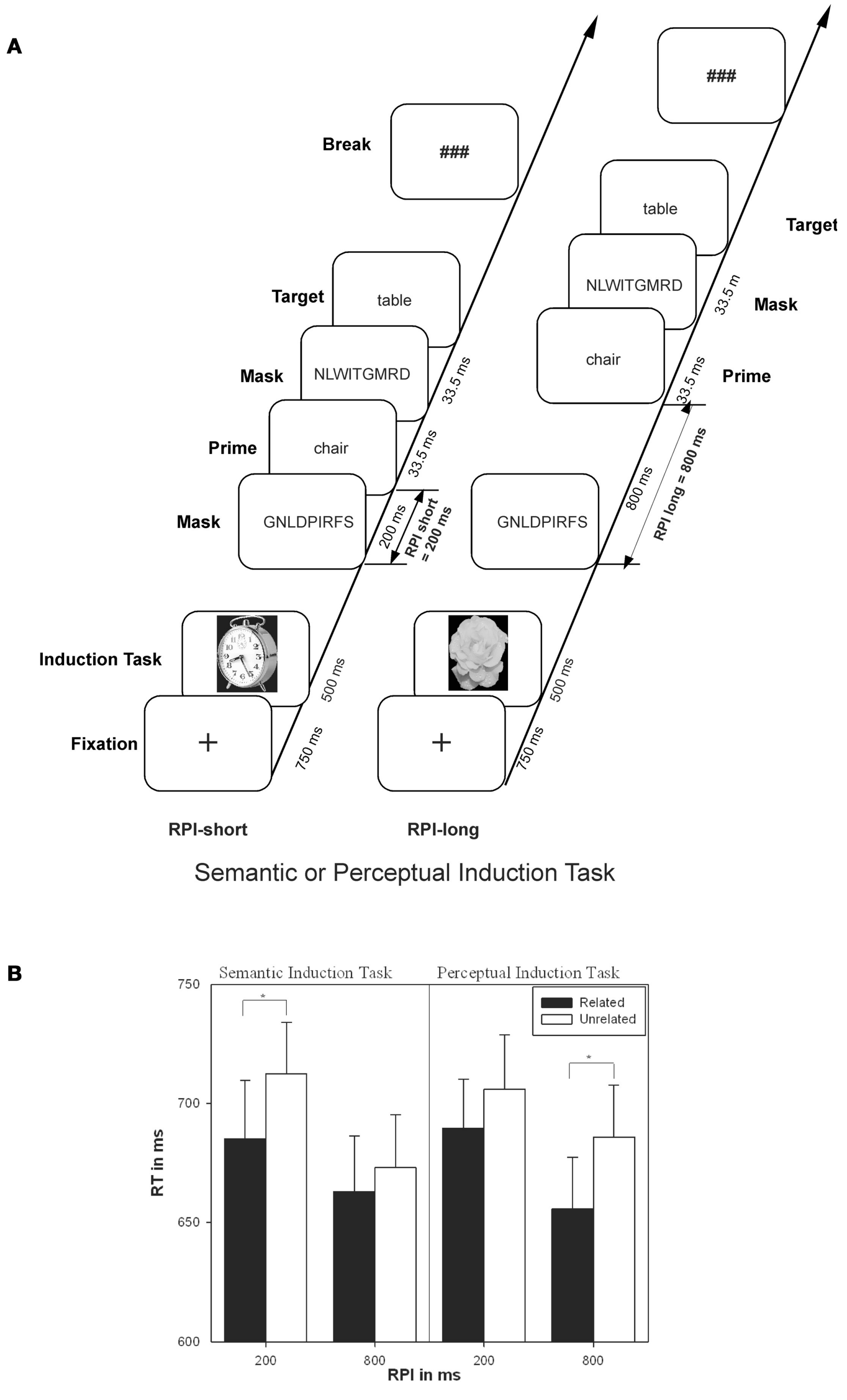

FIGURE 2 | (A) Induction task paradigm in combination with a masked semantic priming task. The masked prime word was presented either 200 ms or 800 ms following the response to the induction task (RPI). The semantic induction task required semantic classification (living/non-living decision) of the pictured object, whereas the perceptual induction task required a perceptual classification of the object (round/elongated shape). Subsequent to masked prime presentation, the target word was presented, which required a lexical decision (word/pseudoword). In the related priming condition, prime and target were semantically related ("table-chair") whereas in the unrelated condition, prime and target were semantically unrelated ("hen-car"). **(B)** Behavioral semantic priming effects of Exp. 1 of the Martens et al. (2011) study. Mean correct response times and their standard error in the lexical decision task, as a function of semantic relatedness, induction task, and RPI. The asterisks indicate significant masked priming effects (difference between semantically unrelated and related conditions) within each induction task/RPI combination. At the short RPI when the task sets were active, significant unconscious semantic priming effects were only obtained following the semantic induction task, but not following the perceptual induction task. At the long RPI when the task sets were inhibited, the opposite pattern was observed: unconscious semantic priming effects were only obtained following the perceptual induction task Modified after Kiefer and Martens (2010) and after Martens et al. (2011).

(see **Figure 2B** for one example). At the short RPI, behavioral and electrophysiological semantic priming effects were obtained when a semantic task set was induced immediately before subliminal prime presentation, whereas a previously induced perceptual task set attenuated priming. In line with the attentional sensitization model, unconscious semantic processing is enhanced by a semantic and attenuated by a perceptual task set. At the long RPI, significant priming was found after the perceptual induction task, but not after the semantic task. This pattern of priming effects at the long RPI suggests that after 800 ms the task set of the induction task had been abandoned and a reconfiguration of the cognitive system in preparation for the upcoming lexical task had taken place (Kiefer and Martens, 2010): semantic pathways are sensitized when the perceptual induction task has been abandoned, but they are desensitized when the semantic induction task has been abandoned. This resulting pattern is compatible with the notion of a backward inhibition mechanism that suppresses irrelevant task sets in preparation of the next task (Mayr and Keele, 2000; Houghton et al., 2009). In line with this interpretation, the RPI did not modulate induction task influences on subliminal semantic priming when the task set of the induction task had to be maintained until the response to the lexical decision task was given (Kiefer, unpublished data). The differential modulatory effects of induction tasks on masked priming as a function of the RPI provide insight in the dynamic nature of cognitive reorganization during task set switching that in turn influences unconscious information processing.

A further recent study using the induction task paradigm examined the attentional boundary conditions for unconscious semantic priming to occur (Adams and Kiefer, submitted). It was assessed whether phonological task sets that are non-semantic in their nature, but do require some form of linguistic processing also reduce unconscious semantic priming. In particular, we were interested whether the effects of phonological induction tasks on subsequent semantic priming were comparable whether the focus was set on phonological processing of the entire word vs. single letters. Before the subliminally primed lexical decision task was presented, participants performed semantic and phonological induction tasks that should either activate a semantic or a phonological task set. Across two experiments, the nature of the phonological induction task (word phonology vs. letter phonology) was varied to assess whether the attentional focus on the entire word vs. single letters modulates subsequent masked semantic priming. In both experiments, subliminal semantic priming was only found subsequent to the semantic induction task, but was abolished following either phonological induction task. The results of this study indicate that attention to phonology attenuates subsequent semantic processing of unconsciously presented primes whether or not attention is directed to the entire word or to single letters. In line with the attentional sensitization model, these findings substantiate the notion that an attentional orientation toward semantics is necessary for unconscious semantic processing to be elicited.

This research on attentional influences on subliminal semantic priming helps to reconcile previous discrepant evidence regarding the automaticity of semantic processing. It has been argued that semantic processing is not automatic, but requires controlled access to conceptual meaning (Henik et al., 1994; Duscherer and Holender, 2002) because semantic priming with visible stimuli has been found to depend on the attentional orientation toward the prime word (for a review, see Maxfield, 1997; for a review, see Deacon and Shelley-Tremblay, 2000): earlier studies on the effects of prime tasks observed reduced or absent semantic priming when participants were required to attend to perceptual letter features of the prime (e.g., a letter search task) and not to its meaning (e.g., Chiappe et al., 1996; Mari-Beffa et al., 2005). These findings were taken as evidence that access to conceptual meaning is confined to a controlled processing mode. However, several other studies demonstrating that unconsciously perceived prime words can elicit semantic priming effects favor the view that semantic processing can also occur in an automatic fashion (Carr and Dagenbach, 1990; Draine and Greenwald, 1998; Kiefer and Spitzer, 2000; Rolke et al., 2001; Kiefer, 2002). This apparent contradiction can be easily resolved if one assumes that unconscious automatic processes depend on executive control through attentional sensitization (Kiefer and Martens, 2010). Our work using the induction task paradigm in combination with a subliminally primed lexical decision task (e.g., Kiefer and Martens, 2010; Martens et al., 2011) shows that even under purely automatic processing conditions, semantic priming is susceptible to executive control as predicted by our attentional sensitization model.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Accumulating evidence demonstrates that various forms of unconscious processing are susceptible to executive control similar to conscious processing: subliminal visuo-motor, and semantic priming effects, prototypical examples of automatic processes, are modulated by executive control factors such as attentional resources, stimulus expectations, action intentions, and task sets. These top-down factors are typically considered to involve executive control mechanisms dedicated to organize action and thought (Norman and Shallice, 1986; Posner and DiGirolamo, 1998). Hence, in contrast to classical theories of automaticity and executive control (Posner and Snyder, 1975; Schneider and Shiffrin, 1977), automatic processes elicited by unconscious visual stimuli are under executive control to some extent. The findings reviewed here support refined theories of automaticity (Neumann, 1990; Naccache et al., 2002; Moors and De Houwer, 2006) in general and the attentional sensitization model of unconscious information processing in particular (Kiefer, 2007; Kiefer and Martens, 2010). According to the attentional sensitization model (Kiefer and Martens, 2010), processing can occur automatically in the sense that it does not depend on conscious awareness and that it is initiated without deliberate intention. However, unconscious automatic processing is modulated by executive control and depends on an appropriate configuration of the cognitive system. Thus, within the light of the attentional sensitization model and the data reviewed in this article, unconscious automatic processing and the notion of executive control are compatible. As shown above, the assumption of attentional sensitization of unconscious information processing can accommodate conflicting findings regarding the automaticity of processes in many areas of psychology and the neurosciences such as visuo-motor (Bub and Masson, 2010), and semantic processing

(Rees et al., 1999; Kiefer and Martens, 2010). The attentional sensitization mechanism may thus apply to many domains and has the explanatory power to account for seemingly contradictory empirical phenomena. Evidence for executive control over unconscious visuo-motor and semantic processing described in the previous sections concerned neuro-cognitive functions predominantly processed in cortical structures. However, if attentional sensitization of unconscious information processing is a general principle, it should also apply to emotional processes, which depend at least in part on subcortical structures (LeDoux, 1996; Rolls, 1999).

IS UNCONSCIOUS EMOTIONAL PROCESSING MODULATED BY EXECUTIVE CONTROL?

Unconscious emotional processes can be investigated with the masked affective priming paradigm. In affective priming, which is assumed to depend on activation of emotional representations, primes and targets (words or pictures) share the same or different (positive, e.g., baby vs. negative, e.g., shark) emotional valence (Fazio et al., 1986; Fazio, 2001). For instance, in an evaluative judgment task (pleasant vs. unpleasant) on visible target stimuli, responses are typically faster when primes and targets exhibit the same emotional valence (for review, see Fazio, 2001). Affective priming activated emotional brain areas including the amygdala, insula, and orbitofrontal cortex (Liu et al., 2010). Although visuo-motor response conflict certainly plays a role for emotional priming during evaluative judgments (Klauer et al., 1997; Klinger et al., 2000), the use of tasks with response-categories that differ from prime-target relatedness demonstrated the involvement of emotional processes in addition to response-based processes (Spruyt et al., 2007; Wentura and Frings, 2008). It should be noted that in most of these experiments stimuli were presented visibly. Nevertheless, these findings are suggestive for executive control influences on unconscious emotional processing as it is shown below.

In the literature on affective priming, there has been a longstanding debate whether emotional information is automatically processed. This debate has been fueled by the observation that affective priming with visible (e.g., Klauer and Musch, 2001; Spruyt et al., 2004) or subliminal primes (Eckstein and Perrig, 2007) frequently disappeared when target tasks other than evaluative judgments (e.g., semantic categorization or word pronunciation) were used. For instance, affective congruency (positive vs. negative valence) of subliminally presented masked prime words elicited only priming effects on the subsequent target decision during an evaluative judgment task, but not during a non-emotional semantic (living/non-living) judgment (Eckstein and Perrig, 2007). Unconscious automatic emotional processing has, therefore, been considered to be a spurious phenomenon (for a discussion, Klinger et al., 2000; for a discussion, Klauer and Musch, 2003). This conclusion is premature, however, because within the light of the attentional sensitization model (Kiefer and Martens, 2010) even unconscious automatic emotional processing depends on an attentional amplification of corresponding processing pathways. When the target task requires attention to non-emotional semantic stimulus features (e.g., living/non-living decision), emotional pathways are desensitized resulting in decreased or absent emotional priming. Hence, for emotional priming to occur, attention must be directed to the emotional stimulus dimension in order to sensitize emotional processing pathways (Spruyt et al., 2009, 2012).

Spruyt and colleagues (Spruyt et al., 2009, 2012) tested the proposed attentional modulation of emotional processing in two studies. In all experiments, emotional priming was probed during a word pronunciation task, which did not explicitly require emotional processing. With such a pronunciation task most previous studies failed to find emotional priming effects (for a review see, Klauer and Musch, 2003). Most critically, in the experiments by Spruyt and colleagues attention was directed to emotional or non-emotional semantic word features in separate participant groups by interspersing different types of induction trials between the priming trials requiring word pronunciation: these induction trials required an emotional or a non-emotional semantic categorization of words and should differentially allocate attention to emotional vs. non-emotional semantic features. Based on the assumption that automatic emotional processing requires an attentional sensitization of emotional pathways, emotional priming during a pronunciation task should only be obtained within the context of emotional induction trials, but not within the context of non-emotional semantic induction trials. Results clearly confirmed these predictions: whether primes were presented unmasked and visibly (Spruyt et al., 2009) or masked and unconsciously (Spruyt et al., 2012), affective congruency between primes and targets facilitated target pronunciation only in the blocks with the emotional induction trials. These findings provide supporting evidence for an attentional modulation of unconscious emotional processing and help to reconcile discrepant findings regarding the automaticity of emotional priming: emotional priming whether elicited by conscious or unconscious stimuli, crucially requires a sensitization of emotional pathways. Thus, attentional sensitization of unconscious processing may apply to emotional brain circuits, which partially involve subcortical structures (LeDoux, 1996; Rolls, 1999), and is not restricted to predominant cortical processes such as visuo-motor or semantic processing. However, as data regarding attentional modulation of unconscious emotional processing are scarce, this research area certainly deserves further investigation.

FLEXIBILITY OF UNCONSCIOUS PROCESSING IN HEALTHY AND CLINICAL POPULATIONS

Our general experimental approach that combines a first task for inducing task sets with a subsequent (subliminally) primed decision task is a useful tool for addressing many research questions regarding executive control of unconscious information processing. It can be used to test whether other forms of unconscious processes than presently investigated in detail (e.g., emotional, visuo-spatial, motor, phonological, orthographic) are similarly susceptible to executive control. It would also be interesting to investigate whether attentional sensitization applies to implicit memory (Schacter, 1995) or implicit learning (Curran, 1998). This would demonstrate that attentional sensitization of unconscious information processing is a general mechanism implemented in the human neuro-cognitive system. The notion of attentional sensitization of unconscious information processing could also help to explain and to further empirically investigate cognitive impairments in clinical populations who occasionally show deficits in unconscious information processing (Kiefer et al., 2009). In particular, conscious control of unconscious emotional processing is clinically highly important because findings in this area might help to design more efficient therapeutic treatment techniques for mood and anxiety disorders. The present approach could also help to elucidate why putatively automatic cognitive processes are strongly modulated by hypnotic induction. For instance, the Stroop interference effect (Stroop, 1935) that depends on a conflict between task-irrelevant automatic processes of word reading and task-relevant processes of color naming (Cohen et al., 1990) is abolished when participants receive the hypnotic suggestion that (English) color words should be conceived as meaningless character strings written in an unknown alphabet (Raz et al., 2006, 2007). Hence, our framework could contribute to a better understanding of the attentional mechanisms underlying the effects of hypnosis in research and therapeutic settings.

Although much progress has been made to demonstrate executive control influences on unconscious information processing using behavioral or neurophysiological measures, its precise functional-anatomical architecture has to be better characterized: the attentional sensitization model assumes that control of unconscious processes is exerted by a prefrontal top-down signal, which influences the sensitivity in brain circuits that process specific information such as stimulus dimensions or features. This assumption can be tested in more detail by means of fMRI and electrophysiological recording techniques.

In conclusion, the executive control influences of unconscious processing reviewed here demonstrates the adaptability of the cognitive system in optimizing ongoing processing toward the pursuit of an intended goal. This research suggests that preemptive executive control of unconscious processes as postulated by the attentional sensitization model coordinates even the unconscious processing streams in congruency with higher-level task representations. This considerably reduces the effort of the cognitive control system to organize behavior because task-incongruent processes are dampened at relatively early stages. Hence, attentional sensitization of unconscious information processing contributes to an effective goal-related adaptation of our cognitive system.

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When planning results in loss of control: intention-based reflexivity and working-memory

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In this review, the authors discuss the seemingly paradoxical loss of control associated with states of high readiness to execute a plan, termed "intention-based reflexivity." The review suggests that the neuro-cognitive systems involved in the preparation of novel plans are different than those involved in preparation of practiced plans (i.e., those that have been executed beforehand). When the plans are practiced, intention-based reflexivity depends on the prior availability of response codes in long-term memory (LTM). When the plans are novel, reflexivity is observed when the plan is pending and the goal has not yet been achieved. Intention-based reflexivity also depends on the availability of working-memory (WM) limited resources and the motivation to prepare. Reflexivity is probably related to the fact that, unlike reactive control (once a plan is prepared), proactive control tends to be relatively rigid.

Keywords: working-memory, intention, reflexivity, preparation, proactive control, prefrontal cortex

INTRODUCTION

Everyday experience suggests that planning may be useful. For example, when going on a trip abroad, it is usually recommended to book the flights, trains and hotels ahead of the trip. Nonetheless, planning is taxing and advance booking requires precious time and effort. Importantly in the present context, advance booking comes at the cost of reduced flexibility since one may not be able to change the hotel, when finding out upon arrival that a better and cheaper hotel is nearby. This conflict between costs and benefits is even more pronounced when planning takes place in parallel with other demanding activities. For example, toward the end of a talk in a conference, one may plan her or his question, yet this very attempt might prevent the person from truly listening to the end of the talk. These informal observations are supported by laboratory research on simple plans. This research suggests that planning (i.e., preparedness) improves action fluency and accuracy, resistance to interference (Braver et al., 2007; Braver, 2012) and the ability to overcome perseverative tendencies (Meiran and Daichman, 2005; Koch and Allport, 2006). At the same time, planning and holding plans in mind have been shown to consume limited processing resources, and thus interfere with other ongoing activity (e.g., Fagot, 1994; Meiran, 2000; Braver et al., 2003; Smith, 2003). Moreover, the fact that planning improves resistance to interference may actually prevent us from processing highly relevant information (e.g., Goschke and Dreisbach, 2008).

In the present work, we discuss an additional drawback of planning, the seemingly paradoxical loss of flexible online action control when the action plan is still pending. We describe this loss of control as "intention-based reflexivity," or simply "reflexivity." By "reflexivity" we mean that a cognitive process is triggered even when it is *not* required or intended *at the given moment* (see also how Bargh and Gollwitzer, 1994; Tzelgov, 1997; Bargh et al., 2001, characterize "automaticity"). Although it may seem self contradictory to refer to the unintended aspects of intended acts, there is no contradiction here. This is because the unintended (possibly partial) execution of the plan may take place prematurely, i.e., before the intended execution, when the plan is still pending[1]. Intention-based reflexivity can potentially have quite dramatic real life consequences such as when a policeman is aiming a gun in anticipation for an attack and accidentally shoots at a civilian who innocently passes by. In the lab, intention-based reflexivity can be studied with simple plans in which a given stimulus or a stimulus-category is linked to a particular planned response. An example for such a plan is to press the right key if the letter is from the beginning of the alphabet and press the left key if the letter is from the end of the alphabet.

NOVEL PLANS, PRACTICED PLANS, AND WORKING-MEMORY

Since plans must be stored and represented in memory, it is critical to consider the likely memory system that is involved. Based on considerations that are detailed below, we distinguish between novel plans and practiced plans. *Novel plans* are plans that have never been executed beforehand, such as the plan to write this paper or the plan to execute a reaction time task for the first time. *Practiced plans* are plans that have been executed beforehand, such as the plan to execute a familiar reaction time task, reach the office, or prepare an omelet. We argue that the kind of processes involved in representing and storing novel and practiced plans are different from one another in important respects. Consequently,

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[1] We use the term "reflexivity" instead of the term "automaticity," because the latter term usually refers to practiced skill and to conditions in which the process is not a part of a pending plan.

the conditions that produce reflexivity in novel plans are quite different from the conditions that produce reflexivity in familiar plans.

The tenet of this paper is that plans are stored in working-memory (WM). However, it is widely appreciated that WM is not a unitary system and there are several different theories describing its subsystems (e.g., Miyake and Shah, 1999). We decided to adopt Oberauer's (2001, 2002, 2010) model [which may be viewed as an extension of Cowan's (1988), model] because of the natural link to reflexivity which this model affords. Following Oberauer, we consider WM as comprising: (1) novel bindings between familiar elements ("region of direct-access," RA) which is a severely limited resource; and (2) temporary heightened accessibility (activation) of familiar representations in long-term memory (LTM), termed "activated LTM" (ALTM), which is much less limited in its capacity (see **Figure 1**). Similar distinctions have been drawn in neuroscience by other theorists including Ruchkin et al. (2003); Postle (2006); Jonides et al. (2008), Bledowski et al., 2010, all suggesting that WM consists of an interaction between attentional systems subserved mostly by prefrontal cortex (PFC) regions and other brain regions involved in perception, semantic processing and action. The link to reflexivity which Oberauer's model affords is related to the fact that, according to Oberauer (2001), RA and ALTM differ not only in their capacity but also in their context sensitivity. While RA is highly sensitive to context, ALTM is not sensitive to context and operates even in inappropriate contexts, i.e., reflexively. To appreciate this link we describe here how Oberauer (2001) operationalized RA and ALTM. In the aforementioned work, Oberauer asked participants to memorize two lists of words and cued them in each trial which list is currently relevant. Following the cue and after a variable interval, a word was presented and the participants' task was to indicate if this probe was a member in the relevant list. Reaction times increased with increasing memory set size, indicating capacity limitations. Additionally, the size of the *irrelevant* list ceased to affect performance when sufficient time (1 s or more) elapsed between the cue and the probe, providing an opportunity to focus on the relevant list. This result is interpreted as evidence that once the participants knew which one of the two lists is relevant, they focused on this list and removed the irrelevant list from RA. As soon as the irrelevant list was removed from RA it ceased to consume its resources.

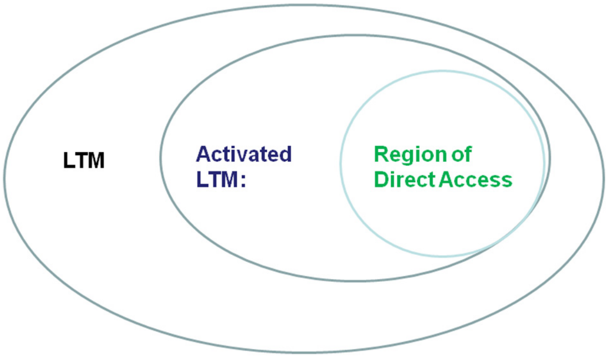

FIGURE 1 | A schematic representation of (our interpretation of) Oberauer's (2001, 2002) model. According to this model, working-memory comprises activated long-term memory representations. The region of direct-access consists of novel bindings between a sub-group of activated long-term memory representations.

The most important finding for the present focus is the *intrusion effect* which, according to Oberauer (2001) indexes ALTM. This effect shows that despite focusing on the relevant list and removing the irrelevant list from RA, participants had difficulty rejecting items that belonged to the irrelevant list. This result indicates that this irrelevant list, while being outside RA, remained highly accessible. In detail, the intrusion effect was defined as the difference in the time taken to reject items from the irrelevant list as compared with completely new items. The intrusion effect was relatively insensitive to set size and the time to focus on the relevant list. Importantly, according to our definition, the intrusion effect indicates the *reflexive* processing of words that belonged to the irrelevant list and thus serves to link ALTM and reflexivity.

THE REPRESENTATION OF PLANS IN WORKING-MEMORY

We now turn to use the distinction between RA and ALTM to describe our hypothesis regarding how plans are represented in WM. Before doing so, we further assume that, because RA resources are scarce (e.g., Cowan, 2001) (1) the use of this resource is avoided as much as possible, and (2) including purging its contents as soon as they become irrelevant or as soon as they can be represented in ALTM.

Based on these considerations, we argue that essential components of novel plans are represented within RA, at least when these plans are meant to be executed in the near future. In order to clarify what we mean by "essential components" let us consider for example the plan to hit the right key in response to a letter from the beginning of the alphabet (see **Figure 2**). This plan has two elements that can be represented in ALTM: the concept

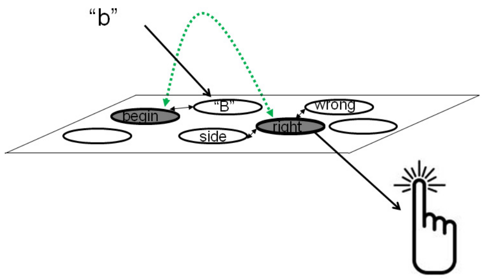

FIGURE 2 | An example for a representation of a simple rule such as IF (the stimulus is a letter from the beginning of the alphabet) THEN (press the right key). When the instructions are given, the long-term memory representations of "letter," "beginning of the alphabet" and "right" are activated. The novel binding between "beginning of the alphabet" and "right" (presented in green color) is in the region of direct-access. When a letter such as "b" is presented, it activates its corresponding representation in long-term memory. Via links in long-term memory, the representation of "beginning of the alphabet" is also further activated, leading to the activation of "right" (via the novel link) and to the key press (via established links in long-term memory).

"right key" and the concept "letter belonging to the beginning of the alphabet." The reason is that these are familiar concepts, hence concepts that are stored in LTM. Based on our assumptions regarding sparing of RA resources, we assume that the representation of these elements *is* taking place within ALTM. However the link between them is novel and must thus be stored in RA. Had this plan been executed beforehand, all the elements of the plan would have been familiar (represented in LTM) and thus the entire plan could be in ALTM. This would be especially true for plans that have been executed at least several times in the past. Thus, while the entire plan can be represented in ALTM when the plan is practiced and familiar, only parts of it can be represented in this system when the plan is new and some elements of the plan must consume the limited RA resources.

REFLEXIVITY OF PRACTICED PLANS

Hommel (2000) provides an extensive review of the evidence for plan reflexivity, which at the time, was exclusively demonstrated using lengthy experiments. Because the experiments were lengthy and the plans remained the same throughout the experiment, one cannot rule out the possibility that the effects reflected practiced rather than novel plans. In the present review, we focus on evidence (1) linking reflexivity to intention and (2) showing that reflexivity of practiced plans depends on ALTM.

An important piece of evidence concerning reflexivity of practiced plans comes from the task-rule congruency effect found in task-switching experiments. This effect has been first demonstrated by Sudevan and Taylor (1987) who asked participants to switch between 2 numerical tasks performed on digits: size (larger/smaller that 5) and parity. Importantly (1) both tasks were executed on the same set of stimuli (the digits 1–9), and (2) the same right-left keys were used. Thus, there were trials in which the two task-rules were associated with the same response (compatible) or with competing responses (incompatible). Sudevan and Taylor found poorer performance in incompatible trials as compared to compatible trials (although this effect was restricted to the parity task). This result shows that, when the parity task was relevant, the currently irrelevant size rule operated reflexively and activated the response that would have been correct had this rule been relevant. Thus, the task-rule congruency effect provides evidence for the reflexivity of the currently irrelevant task and is quite analogous to Oberauer's (2001) intrusion effect. Specifically, in both cases, information that is currently irrelevant but may become relevant in the near future influences performance reflexively. Since this demonstration, there were numerous additional papers that reported this effect (e.g., see Meiran and Kessler, 2008, for a partial review). In this section, we focus on two main issues. One is the evidence linking the task-rule congruency effect (and similar effects) to the intention to execute a given task. The other provides evidence for the involvement of ALTM.

LINKING THE REFLEXIVITY OF PRACTICED PLANS TO INTENTION

While the task-rule congruency effect shows that the irrelevant rule operated reflexively, its mere presence does not indicate that this reflexivity is related to the *intention* to execute this rule. An alternative explanation is that the initial execution of this rule (even during the practice phase of the experiment) leads to the formation of LTM traces, which are known to generate reflexivity (e.g., Logan, 1988). An important piece of evidence linking task-rule congruency effect to intention is the fact that this effect greatly diminishes as soon as participants are told that the task would no longer be required. This result has been demonstrated by several authors including Fagot (1994); Meiran (2000, 2005); Yehene and Meiran (2007); Yamaguchi and Proctor (2011).

Another important demonstration comes from Marble and Proctor (2000, see also Proctor et al., 2000) who compared performance in the Simon task (Lu and Proctor, 1995, for review) in three conditions. In one condition ("pure Simon") participants reacted to the color of stimuli by pressing right and left keys. They had to ignore the irrelevant location of the stimuli. In this condition, a usual Simon effect was found, showing quicker responses when the (irrelevant) location of the stimulus and the location of the responding hand were compatible rather than incompatible. In the critical conditions, the Simon task was intermixed with a location task, which required participants to respond to right-left locations of white stimuli. In one version of the paradigm, the location task was compatible (e.g., if the location is on the right, press the right key) and in the other version of the paradigm it was incompatible (if the location is on the right, press the left key). Marble and Proctor found that, relative to the pure Simon condition, the Simon effect increased (actually, roughly doubled) when the color task was intermixed with a compatible location task. We interpret this result as evidence that being prepared to execute the location task resulted in reflexive application of this plan even in the color task, when it was not required. Interestingly, the Simon effect (observed in the color task) was reversed when the location task was incompatible. This latter result has two important implications. One is that intention-based reflexivity may sometimes be more potent than automatic behaviors (indicated in the standard Simon effect). Specifically, when the Simon task was intermixed with the incompatible location task, the intention to execute the location task generated a tendency for reversed Simon effect while the automatic tendency was to generate a usual Simon effect. In this case, these two tendencies were opposite in direction and the fact that the intention-based tendency dominated suggests that it is more potent than the automatic tendency. The other implication of the reversed Simon effect is that mixing the color task and the location task did not only result in quicker processing of location information in general. If this were true, the Simon effect should have increased even when the location task was incompatible. The fact that the Simon effect had *reversed* indicates that the instructed link between locations and responses (rather than just location information) became reflexive. Memelink and Hommel (2006) ran a similar study but instead of using one location task, they embedded the Simon trials in blocks in which the other task involved switching between up-down and right-left classification of locations. They showed that the horizontal Simon effect increased when the Simon task immediately followed right-left judgments and that the vertical Simon effect increased when it immediately followed up-down judgments. These results further demonstrate the dependence of reflexivity on (prior) intention.

REFLEXIVITY OF PRACTICED PLANS DEPENDS ON ALTM

As mentioned beforehand, we argue that the mere representation of a plan in ALTM provides a sufficient condition for its reflexivity. Thus, the boundary conditions for reflexivity in this case are the same boundary conditions for ALTM representation, namely the prior existence of LTM codes. Meiran and Kessler (2008) noted that the task-rule congruency effect is analogous in many respects to Oberauer's (2001) intrusion effect in the sense that information that is currently irrelevant (but may become relevant soon) is processed nonetheless. To substantiate this analogy, they compared two task-switching paradigms (see **Figure 3**). In one paradigm, participants made up-down and right-left judgments on the location of a target stimulus within a 2 × 2 grid. The responses that were used were the upper-left key (used to indicate UP and LEFT) and the lower-right key (used to indicate DOWN and RIGHT). In this condition, the task-rules were presumably associated with the LTM-stored codes UP, DOWN, RIGHT, and LEFT. In the other version of the paradigm, the display was rotated by 45° as was the arrangement of the response keys. This rotation maintained the spatial relations of the stimuli, the responses, and the compatibility between responses and their corresponding locations. However, the regions within the 2 × 2 grid were no longer associated with the familiar (LTM-based) UP, DOWN, RIGHT, and LEFT regions. They probably were quite novel. The results showed that performance in this condition was slightly impaired relative to the standard, upright condition. The critical findings refer to the task-rule congruency effect. This effect was robust in the standard condition (~90 ms), showing that being prepared to execute one task-rule results in a reflexive application of that rule when the other task-rule is required. Most importantly, there was no task-rule congruency effect whatsoever (0 ms) in the rotated condition. This result shows that the reflexivity of the plan depends on the prior availability of task-related response codes (such as UP and LEFT) in LTM and is absent when these response codes are novel. In a further experiment, the authors showed that the task-rule congruency effect in the rotated condition was re-established after one session of practice and remained stable in the remaining sessions. Arguably, practice resulted in the storage of the formerly novel response codes in LTM. Thus, from Session 2 onward, this aspect of the plan was represented in ALTM.

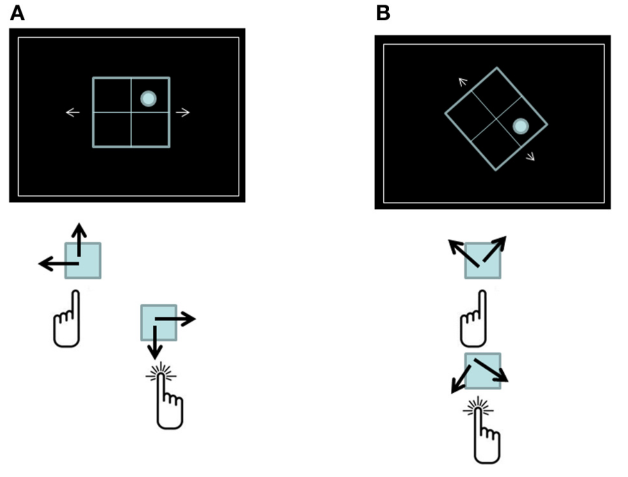

FIGURE 3 | The displays and response-key arrangement used by Meiran and Kessler (2008). (A) The standard display. Participants switched between classifying locations according to a vertical rule (UP vs. DOWN) and a horizontal rule (right vs. left, presented in the figure). The two keys used to respond were associated with UP and LEFT (Key 1) and DOWN and RIGHT (Key 2). The target in this case is incongruent because wrongly applying the vertical rule would have led to an incorrect response (Key 1) instead of the correct Key 2 response. **(B)** A 45° rotation of the display and the key arrangement in which the classification rules involved novel location terms. Here, too, the target is incongruent in the same sense as in **(A)**.

There are two additional pieces of evidence that reflexivity of practiced plans depends on their representation in ALTM. The first line of evidence is insensitivity to preparation. Specifically, Oberauer (2001) showed that the intrusion effect (that operationalized ALTM) was insensitive to the amount of time provided to focus on the relevant word list (and ignore the irrelevant list). Likewise, the task-rule congruency effect has repeatedly been shown to be insensitive to the amount of time allowed to focus on the relevant task and ignore the irrelevant task (e.g., Sudevan and Taylor, 1987; see also Fagot, 1994; Meiran, 1996, 2000, 2005; Meiran et al., 2000; but see Sudevan and Taylor, 1987, regarding preparation-based reduction in task-rule congruency effect after extensive practice). Similarly, as described above, Marble and Proctor (2000) showed that the Simon effect increased in the context of a compatible location task and reversed in the context of an incompatible location task. Importantly, they also showed that the effects remained even when participants received cues indicating which task is currently in effect. This last result shows that participants were unable to remove the plan to execute the location task from ALTM just as Oberauer's (2001) participants were unable to remove the irrelevant list from ALTM.

The last piece of evidence is the lack of sensitivity of the task-rule congruency effect to WM load, a manipulation which presumably exhausts RA limited resources. The rationale here is that if the exhaustion of RA resources does not influence the task-rule congruency effect then this effect must be based on other forms of representation. In detail, Kiesel et al. (2007) studied the task-rule congruency effect in an experiment involving 2 numerical tasks (magnitude and parity). The trials were executed in the retention interval of 2 vs. 5 letters (the WM load manipulation). These authors found that this load manipulation, while being effective (seen in generally poorer performance) did not influence the task-rule congruency effect. Kessler and Meiran (2010) raised the possibility that the load task used by Kiesel et al. might have been ineffective because it may have involved a different WM compartment as that used to store the task plans (Oberauer, 2010, see below). Thus, they used additional tasks as their load manipulation instead of memorizing items. In their experiments, the task-rule congruency effect was measured in the shape and color tasks, performed on colored shapes. The load tasks were 1 or 3 numeric tasks, performed on digits (Experiments 1 and 2) or size, fill and line thickness tasks, performed on completely different shapes. In none of the experiments was there a modulation of the task-rule congruency effect under heavier load, thus substantiating Kiesel et al.'s (2007) conclusions.

REFLEXIVITY OF NOVEL PLANS

According to prevalent theorizing (e.g., Schneider and Shiffrin, 1977; Logan, 1988), reflexivity/automaticity results from extensive and consistent practice. These theories do not postulate reflexivity for novel plans. Moreover, Oberauer's (2001) theory link reflexivity to ALTM but not to the RA. These considerations suggest that plans in RA might *not* be reflexive. However, there is a much older theory in psychology, *Prepared-Reflex* (PR) (Exner, 1879; Woodworth, 1938; see Logan, 1978; Hommel, 2000), suggesting that reflexivity of novel plans is not only possible, but may actually represent the typical scenario (see e.g., Folk et al., 1992, 1993, 1994; Remington and Folk, 2001; Pratt and Hommel, 2003, for related ideas concerning the direction of attention. See Bekkering and Neggers, 2002; Fagioli et al., 2007a,b; Wykowska et al., 2009, for evidence suggesting that reflexive attention orientation may actually represent reflexive action-intentions, as reviewed by Hommel, 2010). According to the PR theory, the representation of novel plans in RA in advance of task execution may be sufficient to cause these plans to become reflexive.

There have only been a few studies that have examined the reflexivity of truly novel plans. The few that did have provided evidence favoring the PR theory by showing that novel plans can be reflexive. These studies also suggest some important boundary conditions for novel plan reflexivity. We review them chronologically. As can be seen, the methodology improved gradually, allowing various alternative explanations to be more carefully ruled out.

de Houwer et al. (2005, Experiment 2) adopted an approach in which plan reflexivity was measured when the participants held the plan active in anticipation of its execution. Specifically, these authors instructed participants to be ready to react to the words "right" and "left" (as well as to equivalent arrows) with the utterances "bee" and "boo." They additionally asked the participants to use these same responses to indicate the color in which rectangles were presented. These rectangles appeared on the right or on the left despite of the fact that location was irrelevant. Importantly, during task performance there were actually no location words or arrows presented, meaning that the plan to react to location information was not practiced. Of interest was whether holding in mind the novel plan to react to locations with utterances would be reflexive. Reflexivity was measured in the color task by comparing compatible and incompatible trials, defined according to whether the reaction to (the irrelevant) location would have been the same as that for (the relevant) color. de Houwer et al. found a significant compatibility effect in their experiment (compatible RT $<$ incompatible RT), indicating the reflexivity of the plan to react to locations. The major limitation of this study has to do with the fact that the plan might not have been truly novel and that reflexivity was built in the course of the experiment. This could have happened if the participants occasionally (and erroneously) reacted to the location of the colors instead of reacting to colors. A similar criticism (with respect to plan novelty) applies to studies that have examined subliminal response priming effects, which are not reviewed here (e.g., Eimer and Schlaghecken, 1998; Kunde et al., 2003). Showing a compatibility effect immediately (i.e., in the very first-trials) after the task was instructed would have ruled out this possibility. Below we review two series of studies in which this prerequisite was met.

Wenke et al. (2007) asked participants to be prepared to execute a new speeded letter classification task in each trial (Task 2). This task involved an arbitrary mapping of two letters to the right-left key presses (e.g., N → left, K → right). Of interest is that, while being prepared to execute this letter classification task, the participants were given another task (Task 1) in which a pair of letters in different sizes was presented (e.g., "NK"). This task was introduced in order to assess plan reflexivity with responses indicated by pressing the spacebar once or twice. In Experiment 1, the participants were required to indicate the location of the larger letter in the pair while in Experiment 2 they indicated the color in which the larger letter was presented. There were compatible (e.g., "NK"), incompatible (e.g., "KN") and neutral (e.g., "FB") trials. The results indicated slightly quicker reactions to compatible trials than incompatible trials, and were thus interpreted as evidence that the instructions were sufficient to bind letter identity and response location (e.g., bind the letter "N" with the left side). However, these results do not provide evidence that the instructions for the letter classification task (Task 1) operated reflexively. This is partly because the responses in Task 2 (right vs. left key press) were different than the responses in Task 1 (single vs. double press of the space bar), meaning that Task 1 did not enable the full application of Task 2 instructions.

Cohen-Kdoshay and Meiran (2007) study overcomes the aforementioned shortcoming. These authors used a variant of the flanker paradigm (Eriksen and Eriksen, 1974) in which a centrally presented target was flanked by response-(in)compatible noise characters that were always physically different from the target. For example, when classifying target letters as belonging to the beginning/end of the alphabet, the stimuli "WBW" and "EBE" are incompatible and compatible, respectively. While the required response ("beginning of the alphabet") is the same in both of them because the target letter is "B," this target is flanked by letters that are either associated with the same response as the target ("E") or with an opposite response ("W") (see **Figure 4**). The novel aspect about Cohen-Kdoshay and Meiran's design was that a new stimulus set (and stimulus-response binding) was introduced in every experimental block. The key finding was a large (∼60 ms) flanker compatibility effect (called first-trials flanker compatibility effect, or "first-trials compatibility effect," for short) that was found in the first block of eight trials immediately following the instructions. By introducing additional procedural changes, Cohen-Kdoshay and Meiran (2009) further showed that the first-trial compatibility effect was found in the very first-trial following the instructions, and that it was numerically larger than the compatibility effect in subsequent trials in the first mini-block of trials. This first-trial(s) compatibility effect indicates reflexivity because the processing of the flankers led to response activation despite the explicit requirement to ignore them. It also overcomes the issue of plan novelty, since the effect was measured immediately after the instructions. Additionally, the methodology is improved over the Wenke et al.'s (2007) study, because in that study the compatible condition constituted a physical representation of the instructions in the sense that the letter associated

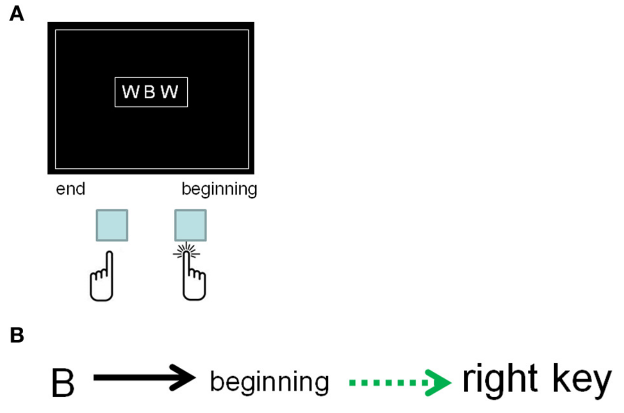

FIGURE 4 | The display used by Cohen-Kdoshay and Meiran (2007). **(A)** The participants were required to respond to the central letter and ignore the flanking letters. A new rule was instructed in each experimental block. This rule was (for example) to press the right key if the letter came from the beginning of the alphabet and to press the left key if it came from the end of the alphabet. The stimulus in the figure is incongruent because the flankers are associated with a competing response (Congruent displays could be "DBD," for example). **(B)** The representation of the instructions, according to our framework consists of activated long-term memory and the region of direct-access (in green), as in **Figure 2**.

with the right key appeared on the right and the letter associated with the left key appeared on the left. This aspect makes it possible that the quicker (slower) responses reflected a (mis)match between the display and the instructions. No such criticism could apply to Cohen-Kdoshay and Meiran's experiments. Thus, there is greater confidence that the representation of the instructions in RA has reflexively generated a response tendency (or at least, the response identity, e.g., see Hommel, 1998) for the flankers even before those flankers had ever been practiced as a target response. Nonetheless, there still remains an alternative explanation according to which the flankers primed target identity processing (rather than have caused response generation). This alternative account holds because the flankers were semantically associated with the target (e.g., both belonged to the beginning of the alphabet). We do not think this alternative account is likely to be correct because the flanker compatibility effects quickly diminished in the course of the block, a trend that is not expected for semantic priming.

Finally, there is one study that tried but failed to show evidence for novel plan reflexivity. The findings of this study point to important boundary conditions for novel plan reflexivity as discussed below. Waszak et al. (2008) employed a task-switching design in which participants switched between color classification and shape classification. Importantly, some of the (irrelevant) colors used in the shape task and some of the (irrelevant) shapes that were used in the color task were only instructed and were never presented as targets. These authors found a reliable task-rule congruency effect. However, the task-rule congruency effect was only found for the irrelevant features that also were presented as targets (in other trials), but not for the irrelevant features that were merely instructed (and never responded to as targets). Thus, holding the plan to react to a given color/shape in a certain manner was insufficient for the reflexive application of this plan. The potential reasons for this null finding are discussed now.

BOUNDARY CONDITIONS

The extant literature suggests three boundary conditions for the reflexivity of novel plans. The first is the availability of RA storage resources. The second boundary condition is that the planned task and the task in which reflexivity is measured must be considered to be part of the same processing event. The final condition is the motivation to maintain high preparedness to execute the planned task. We will discuss each one of these factors in turn.

Availability of RA storage resources

The fact that RA storage resources must be available has been demonstrated by Cohen-Kdoshay and Meiran (2007, Experiment 4) who showed that the first-trial compatibility effect was eliminated when RA was loaded by secondary task instructions. Specifically, in addition to instructing participants to carry out a new classification task, each block also included a novel go-nogo to be performed on rare occasions. This task involved clearly distinguishable target stimuli (numbers or number words) and required a "go" response (pressing the spacebar with both thumbs) if the stimulus met a certain criterion (such as being divisible by 3). In these conditions, the first-trial compatibility effect was eliminated, suggesting that only when the novel plan is held in its entirety in RA, reflexivity is found. We have recently addressed an alternative account to this finding according to which the load task did not exhaust storage space, but instead merely introduced increased multitasking demands. In order to rule out this account, Meiran and Cohen-Kdoshay (2012) compared three groups of participants. In one group, there was no additional load. This group showed the usual first-trial compatibility effect. In another group, there was a load task that was changed between blocks, as in Cohen-Kdoshay and Meiran (2007) fourth experiment. The first-trial compatibility effect was eliminated (actually, slightly reversed) in this group, thus replicating our previous work. Of interest is the third group in which the go-nogo task remained the same throughout the experiment. In this group, the load task increased multitasking demands but did not load RA (because the load task could have been represented in ALTM). This group showed a first-trial compatibility effect that was equivalent to that found in the group without load. These results show that what is critical is the representation of the plan in RA.

Ellenbogen and Meiran (2008) studied the involvement of RA in the backward compatibility effect (Hommel, 1998). In their experiments, participants made speeded responses to the letters H and S presented in different colors. The primary task was color classification which was made using right and left key presses. The secondary task that was executed immediately afterwards was letter classification in which the (arbitrarily mapped) responses were the (Hebrew equivalents) of the utterances RED and GREEN. The logic was that executing Task 1 while being prepared to execute Task 2 would lead to compatibility effects such that if the color of the stimulus is the same as the utterance made to letter identity, reaction would be relatively quick. This compatibility effect was termed "backward compatibility" by Hommel. Of interest is the load manipulation used in this study, which was the number of possible colors (and thus, the number of color-key associations). When the load was low (two colors) or moderate (four colors) there was a robust backward compatibility effect (thus completely replicating Hommel and Eglau, 2002). However, when the load was extreme (six colors) the backward compatibility effect was eliminated. In a further experiment, the authors showed that the critical factor was not the number of colors, but the number of color-category—to—response rules. The fact that extreme load was needed to eliminate reflexivity already provides evidence that a few dozens of executions are sufficient to reduce the dependence on RA such that extreme load is needed in order to remove plan reflexivity.

Inclusion in an event

We suggest the principle that if a person has a plan in mind to execute a task, this forms an event which lasts from the point of planning to the point of plan execution. We will refer to it as the plan-to-execution event. We further suggest that the measurement of reflexivity of a plan must take place during the plan-to-execution event.

Although the term "event" is rather elusive, there is marked agreement between observers regarding event boundaries, and considerable objective support for the psychological reality of these boundaries (e.g., Zacks et al., 2007). Our notion regarding plan-to-execution events is supported by findings from this literature including those indicating that a goal change demarks event boundaries (Zacks and Swallow, 2007) and the evidence suggesting that the contents of RA are refreshed (i.e., updated) at these boundaries (e.g., Swallow et al., 2009) presumably in order to free these scarce resources as soon as possible.

Ellenbogen and Meiran (2011) showed evidence that plan reflexivity takes place only during the plan-to-execution event. These authors used the backward compatibility effect (described above) as an index of reflexivity. In this paradigm, the relevant plan-to-execution event (of Task 2) presumably starts before Task 1 is executed, when participants are ready to execute both tasks in close succession. However, subtle environmental cues may be sufficient to start planning for Task 2 only after Task 1 has already been performed. We specifically refer to cues indicating that a goal has been achieved. In one of Ellenbogen and Meiran's experiments (see **Figure 5**), participants were presented with a colored square and a digit. They then reacted to the color by a right/left key press and to the magnitude of the digit by saying "right" or "left." After responding to both of these stimuli (Tasks 1 and 2, respectively), a second digit was presented and Task 3 was performed. Like in Ellenbogen and Meiran (2008) study, described above, Task 1 was used to assess the reflexivity of the plan to execute Task 2 because Task 2 responses (saying "right" or "left") were either compatible or incompatible with the key press made in Task 1. Task 3 was added in order to manipulate the duration of the plan-to-execution event. In the experimental group ("grouped"), the color of the square indicated whether Task 3 would involve adding the two digits or subtracting the third digit from the second digit. Under these conditions, color processing (Task 1) belonged to the same plan-to-execution event as Task 2 because this event ended only when Task 3 has been executed. In the control group, the colored square did not serve as a task cue for the two digits and thus Task 1 belonged to one event while Task 2 and Task 3 belonged to different event. (In this group, the cue for Task 3 was a minus or a plus sign that appeared below the second digit.) Because the second digit (the stimulus for Task 3) was presented only after the response to Task 2 was made, the display and the tasks were identical for the two groups until Task 2 ended, which is when backward compatibility effects were assessed in order to measure plan reflexivity. The results indicated a backward compatibility effect (in Task 1, as usual) but only in the experimental group and not in the control group. This result shows that the plan to execute Task 2 (whose reflexivity was assessed) was retrieved into RA only when Task 1 (in which reflexivity was assessed) was a part of the same plan-to-execute event as Task 2.

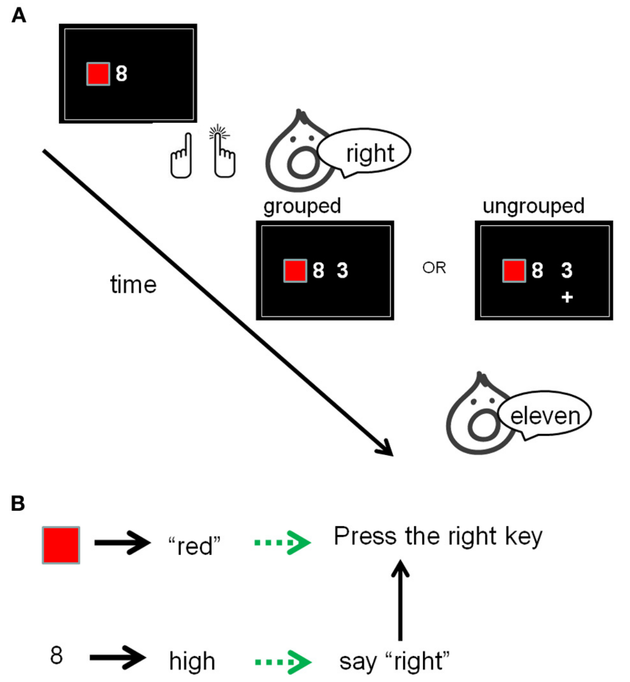

FIGURE 5 | Ellenbogen and Meiran's (2011) fourth experiment. (A) Stimuli 1 and 2 were first presented, then Responses 1 (key press) and 2 (vocal) were given, then Stimulus 3 was added, then Response 3 was given. The color in Stimulus 1 indicated if Task 3 was addition or subtraction (or the +/− sign in the ungrouped condition). **(B)** The representation of the instructions for Tasks 1 and 2 according to our framework were held as a blend of activated long-term memory (the concepts written in black as well as overlearned links between them) and region of direct-access (green).

Motivation

The motivation to hold the plan in mind seems important as well because when motivation is lacking, the plan may not be represented in RA, for example. To our knowledge, the only motivation-relevant findings are by Wenke et al. (2009) using the same paradigm as Wenke et al. (2007), described above.

Wenke et al. (2009) compared conditions that are associated with differential motivation levels to prepare an action in advance. For example, one such condition involved frequent omission of the requirement to execute the plan. Specifically, their paradigm involved preparing for a choice reaction time task (Task 2) and executing another task (Task 1) that was used to assess plan reflexivity. When Task 2 was frequently omitted, this presumably lowered participants' motivation to prepare toward this task. Accordingly, there was no evidence that the plan to execute Task 2 was reflexive in these conditions. These results suggest that being motivated to maintain high readiness to execute a task is a precondition for reflexivity. Nevertheless, this boundary condition awaits further testing in which motivation levels are manipulated directly (e.g., with incentives).

Individual differences

An additional potential precondition is individual differences in RA capacity, a factor that has not yet been examined. Suggestive evidence comes from Wilhelm and Oberauer (2006) who, in an individual differences study, found a correlation between WM capacity and reaction time. Of interest is the key finding in this paper showing that the aforementioned correlation was significantly higher when the reaction time tasks involved an arbitrary stimulus-response mapping (which presumably would be held in RA, at least until sufficient practice had accrued) as compared with a non-arbitrary (and compatible) mapping in which response identity can be directly retrieved from LTM. Nonetheless, the authors did not examine performance on the tasks immediately following the instructions and therefore it is difficult to tell with certainty if these findings relate to novel task representation.

Relevance of the boundary conditions to the null result of Waszak et al. (2008)

After listing the boundary conditions for plan reflexivity, it becomes clear why there was no evidence for reflexivity in Waszak et al.'s (2008) study. Specifically, in their study, there might not have been sufficient motivation to maintain readiness to react to stimulus values that never served as targets precisely because they never served as targets, a fact that could probably have been detected already at the beginning of the experiment, after a few dozen trials. Additionally, the limited RA storage capacity might have been exhausted because of rather high cognitive demand, involving many stimulus-response pairs and two tasks. Finally, the measurement of reflexivity was performed outside the plan-to-execution event. Specifically, when the task-rule congruency effect was assessed in the color task (for example), it reflected the readiness to execute the shape task, but the shape task was executed in other trials and thus belonged to different events.

PROCEDURAL VS. DECLARATIVE WM

While we adopted Oberauer's (2001, 2002) model, more recently, Oberauer (2010) further suggested that WM has two distinct compartments with analogous structure, procedural WM and declarative WM. Our description of WM subcomponents accords well with Oberauer's (2010) characterization of declarative WM. However, Oberauer's (2010) characterization of procedural WM indicates that PR behaviors are related to the procedural compartment and not the declarative compartment. We think that given the current knowledge, it is difficult to decide whether a separate procedural WM exists, although the available evidence seems to favor a domain-general view rather than a distinction between two WM systems. One line of evidence concerns individual differences in WM and reaction times (assuming that reaction times are related to procedural WM). Specifically, Schmiedek et al. (2007) tested participants with various declarative WM measures and also tested them on choice reaction time tasks, all involving arbitrary stimulus-response mapping. Using a structural equations modeling approach which permits estimation of correlations between latent variables (as opposed to observed measures), these authors found a strong correlation ($r = 0.90$) between an aspect of the reaction time distribution and WM. Wilhelm and Oberauer (2006) results, described beforehand, lead to a similar conclusion. Along a similar line, Hartstra et al. (2011) who examined the brain areas involved in the representation of novel instructions found that the very same brain region (left lateral PFC) subserved novel task instructions and the storage of novel object-color associations. These results support a domain-general view rather than a separation between procedural and declarative WM.

POSSIBLE NEURO-COGNITIVE MECHANISMS

A theoretical framework that can potentially explain the difference between novel and practiced plans is the dual-mechanisms of control account developed by Braver et al. (2007, 2009; Braver, 2012). This framework distinguishes between two modes of cognitive control: proactive and reactive. The *proactive control* mode involves preparatory activation and sustained maintenance of goal-related information triggered by advance contextual cues (i.e., task instructions). It contrasts with *reactive control*, involving transient, stimulus-triggered retrieval of goal-related information that is based on conflict detection or bottom-up associative links. Importantly, prior work has demonstrated variability or flexibility in these control modes, linked to (sometimes subtle) features of the task or stimuli, as well as stable individual differences (Braver et al., 2007; Braver, 2012). This variability has been detected in terms of brain activity dynamics, using fMRI methods. Thus, under task conditions preferentially associated with proactive control, anticipatory and sustained intention-related activity has been observed in the lateral PFC. In contrast, under conditions involving reactive control, activity was transient, stimulus-triggered and involved not only the lateral PFC, but also brain regions associated with conflict detection (i.e., anterior cingulate cortex) and episodic/associative retrieval (i.e., lateral parietal cortex, anterior PFC, and medial temporal lobes). Additionally, other work has suggested that proactive control is preferentially engaged for the preparation of action-intentions, i.e. plans (vs. preparatory attention; Ruge et al., 2009, 2010). The dual-mechanisms of control framework, therefore, suggest that the critical difference between proactive and reactive control is not just which brain regions are engaged, but moreover the temporal dynamics of activation. Here, we further suggest that plan novelty might also be a potential key feature that promotes proactive control, whereas practiced plans might rely more on reactive control. One reason why this may be so is that performing a novel task requires sustained binding of the task elements (see below) and thus RA. However, dealing with familiar tasks may be performed "on the fly" by retrieving the already stored binding of task elements. This view predicts that novel plans would be associated with increased anticipatory (i.e., prior to plan implementation) activation within lateral PFC, whereas practiced plans should be associated with greater transient post-stimulus activation (in these and other regions). This would be in line with the idea that novel plans are in a stronger PR type state than practiced plans.

Only very few studies have compared novel and practiced tasks directly. Cole et al. (2010) developed a paradigm that enabled comparison of novel and practiced tasks by permuting a set of rules into many novel rule combinations (i.e., tasks), creating a large space of possible tasks (64). The rules used fall into three categories: semantic (e.g., "is it green?"), decision (e.g., "is the answer to both words the same?"), and response (e.g., "if true, press your left index finger"). Thus, one of the 64 tasks could be, "If the answer to "is it green?" is the same for both words then press your left index finger." By utilizing 64 different tasks, it is possible to obtain reliable estimates of novel task learning, by examining first-trial performance on each of the tasks. Further, a subset of the 64 tasks is extensively practiced, such that novel and practiced tasks can be directly compared while controlling for the particular stimuli and rules used. Cole et al. found (using functional MRI; fMRI) that practiced task preparation activated the anterior PFC first, then the dorsolateral PFC. In contrast, they found a reversal of this pattern for novel tasks, suggesting that practiced tasks involve a top-down task set retrieval (from LTM) process, while novel tasks involve a bottom-up task set formation process. Thus, it was the pattern of relationship between the lateral PFC and other brain regions (anterior PFC, in this case) that distinguished between practiced and novel tasks, somewhat in line with Braver et al.'s distinction between proactive and reactive control. Using a variety of tasks with unique visual stimuli, Ruge and Wolfensteller (2010) also observed that PFC (among other regions) was involved in novel task learning.

Continuing this line of investigation, Cole et al. (2011) used multivariate pattern analysis of fMRI data to identify the presence of specific rules within PFC. They found that PFC activity patterns associated with specific rules during practice were also present during novel task preparation and execution. This suggests that the PFC gains much of its flexibility by *rigidly* applying old but highly practiced activity patterns to novel contexts. The present review suggests that rigidity may be a general feature of highly prepared states rather than being restricted to the application of familiar rules.

In a related study, Gilbert et al. (2012) used a similar analysis approach to examine the content of delayed intentions. They observed a sustained, intention-related increase in anterior PFC activity, and increased connectivity of this region with posterior cortex regions that showed content-specific representation. This suggests a potentially interactive model, in which sustained PFC input may be needed to shift posterior cortex representations from the ALTM to RA component of WM or alternatively, to bind the novel pattern of LTM representations in posterior cortex, in accordance with how we defined RA.

Our notion concerning reflexivity of novel plans may seem counterintuitive. Nonetheless, it accords with current theorizing concerning the nature of PFC representations. Specifically, these representations are described as being highly flexible in the sense of representing any novel combination of familiar elements (e.g., O'Reilly et al., 1999; Miller and Cohen, 2001). However, PFC representations are also believed to be highly resistant to interference. What we suggest is that this resistance to interference comes at the cost of losing online flexibility. In this regard, incorporating rapid contextual changes into the existing RA representation may require the formation of an entirely new representation (cf. Kessler and Meiran, 2006, 2008) This new activation-based RA representation is likely fragile (i.e., incoming activity can destroy it), and so it is "locked in" to reduce interference, making us somewhat less responsive to immediate contextual changes. Consistent with this idea, Duncan (2010) suggested that encoding in PFC (and other brain regions which form the Multiple Demand network) is based on the *pattern* of neuronal activation. He further argues that when the represented content changes, so does the *pattern* of neuronal activation. Similarly, O'Reilly et al. (2003) suggested a coarse and distributed coding system. Since the neurons in this coding scheme encode conjunctions of elements, a change in the context seems to again require a change in activation over many neurons. Singer and Gray (1995) and others suggest that novel representations consist of synchronous neuronal firing, which, for WM representations is presumably supported by the PFC (e.g., Ruchkin et al., 2003). Updating such a representation seems to require generating a new pattern of synchronous activity. Braver and Cohen (2000) suggest that PFC representations are updated only on specific occasions, determined by the dopamine-controlled gating system, again implying that there are periods in which representations cannot be updated. Regardless of the differences, all of the theories suggest that RA-based representations, while being extremely flexible in the sense that they can be entirely novel combinations of elements, are inflexible in their responsiveness to rapid contextual changes in the environment, which according to the present thesis is what characterizes intention-based reflexivity.

CONCLUSIONS

In this brief review, we have presented evidence that the intention to carry out a simple plan in the near future may result in paradoxical loss of control, such that the intended plan may be (at least partly) executed prematurely and inappropriately. We distinguished between two types of plans based on the WM compartment that is probably used for their storage. Planning to execute a familiar task may be entirely based on ALTM, thus preserving the scarce RA capacity resources. However, when the plan is novel, aspects of it are probably represented in RA. We further showed that different boundary conditions apply to the reflexivity of novel and practiced plans and suggested the likely neuro-cognitive mechanisms that are being involved. We thus conclude that plan reflexivity provides clues as to the mechanism underlying the mind's tremendous flexibility during preparation. It seems that whatever mechanism gives us this gift of mental flexibility to allow for rapid novel planning also takes away flexibility as a new plan is prepared to be executed.

The hypotheses that we outlined in this paper lead to many future research directions that stem from currently unresolved questions, such as: is plan reflexivity a (perhaps unwanted) side-effect of planning or is it (also) associated with benefits? In this regard, Gollwitzer (1999) suggested that reflexive plans are more likely to get successfully executed, in part because of reduced dependence on endogenous control inputs. (This hypothesis is still hotly debated, e.g., see Brandstätter et al., 2001; Smith, 2003 vs. e.g., McDaniel and Scullin, 2010.) Additionally, despite the relatively clear evidence that novel and practiced tasks are subserved by different patterns of brain activity, it is unclear at present whether these differential patterns are related to plan reflexivity. Finally, while we suggested that plan reflexivity is a feature of proactive control, this is merely a speculation at this point and further research is needed to provide direct support for it.

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Conscious and unconscious processes in cognitive control: a theoretical perspective and a novel empirical approach

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Controlled processing is often referred to as "voluntary" or "willful" and therefore assumed to depend entirely on conscious processes. Recent studies using subliminal-priming paradigms, however, have started to question this assumption. Specifically, these studies have shown that subliminally presented stimuli can induce adjustments in control. Such findings are not immediately reconcilable with the view that conscious and unconscious processes are separate, with each having its own neural substrates and modus operandi. We propose a different theoretical perspective that suggests that conscious and unconscious processes might be implemented by the same neural substrates and largely perform the same neural computations, with the distinction between the two arising mostly from the quality of representations (although not all brain regions may be capable of supporting conscious representations). Thus, stronger and more durable neuronal firing would give rise to conscious processes; weaker or less durable neuronal firing would remain below the threshold of consciousness but still be causally efficacious in affecting behavior. We show that this perspective naturally explains the findings that subliminally presented primes induce adjustments in cognitive control. We also highlight an important gap in this literature: whereas subliminal-priming paradigms demonstrate that an unconsciously presented prime is sufficient to induce adjustments in cognitive control, they are uninformative about what occurs under standard task conditions. In standard tasks, the stimuli themselves are consciously perceived; however, the extent to which the processes that lead to adjustments in control are conscious or unconscious remains unexplored. We propose a new paradigm suitable to investigate these issues and to test important predictions of our hypothesis that conscious and unconscious processes both engage the same control machinery, differing mostly in the quality of the representations.

Keywords: cognitive control, conflict monitoring, conscious, medial prefrontal cortex, prefrontal cortex, subliminal priming, unconscious

Humans and other animals adjust their behavior flexibly in the pursuit of goals. Cognitive control mechanisms are the set of processes that allow for such flexible adjustments. For instance, cognitive control is necessary to override automatic or habitual responses when they conflict with current goals—a process that has been long studied through tasks such as the Stroop or Simon Spatial Incompatibility tasks. The common ground of these tasks is the experimental induction of *conflict* between a prepotent response and a weaker response that is correct according to the task goal. Often this conflict is induced by different features of the same stimulus (e.g., the location of an arrow relative to the midline and the direction in which the arrow is pointing), with one of the features stimulating a prepotent response tendency (e.g., a left response to an arrow presented to the left of the midline) and the other feature indicating the response that is correct according to the task goal (e.g., a right response to a right-pointing arrow, even if it is presented to the left of the midline). To resolve the conflict induced by these *incongruent* stimuli, cognitive control mechanisms provide top-down biases that facilitate the goal-directed response over the more automatic one (Miller and Cohen, 2001; Maia and Cleeremans, 2005). Conscious will has been classically assumed to govern this type of controlled processing: i.e., voluntary, conscious processes would be required to select the goal-directed response.

The detection and resolution of conflict, importantly, are nonstatic processes that depend heavily on the task context. An effect common to all conflict tasks, the *conflict-adaptation* effect, illustrates this contextual dependency. Conflict adaptation is the improvement in the resolution of conflict following the experience of conflict. Such adaptation typically occurs on a trial-to-trial basis (Gratton et al., 1992; Egner, 2007) but it also arises on a blockwise basis (Tzelgov et al., 1992; Carter et al., 2000). The description of the conflict-adaptation effect prompted the development of influential models of cognitive control that accounted for both conflict resolution and its contextual adaptability. The influential conflict-monitoring model (Botvinick et al., 2001), for example, proposed that a monitoring system, putatively located in the anterior cingulate cortex (ACC) and activated by conflict, signaled to the prefrontal cortex (PFC) the need to further boost top-down biases that enhanced task-relevant information-processing pathways. As a result, task-relevant responses would be facilitated following conflict, and conflict resolution would, therefore, be more efficient, thereby explaining the conflict-adaptation effect. Despite some findings that are at odds with this model and the existence of several competing theories (Holroyd and Coles, 2002; Brown and Braver, 2005; Critchley, 2005; Carter and van Veen, 2007), substantial evidence supports several aspects of this model (MacDonald et al., 2000; Botvinick et al., 2001; Kerns et al., 2004; Kerns, 2006; Carter and van Veen, 2007).

The conflict-monitoring model does not itself address the potential role of consciousness in controlled processing [despite the close relation between similar cognitive-control models and models of consciousness (Maia and Cleeremans, 2005)]. We suggest, however, that one can take advantage of the model's clearly delineated mechanisms to consider which cognitive control mechanisms might be dependent on conscious processing and which might potentially operate unconsciously. Such an approach allows us to move from simple descriptive questions about the conscious or unconscious correlates of behavior to more detailed questions about the potential implication and roles of conscious and unconscious processing in the mechanisms of cognitive control. For example, we can reformulate the question of whether conflict adaptation requires conscious knowledge to the more mechanistic question of whether the detection of conflict by the ACC and the subsequent strengthening of control by the PFC require conscious knowledge. Importantly, such a reformulation is not merely "cosmetic," as it raises multiple empirically testable questions about the dependence of the different components of the model on conscious versus unconscious processes. For example, does the detection of conflict by the ACC need to become conscious for conflict adaptation to occur? If so, what level of conscious knowledge is required: explicit knowledge about the preceding conflict or just a vague feeling that performance is not going well? And what is the relationship between ACC activation with conflict and explicit knowledge of conflict? Does the ACC form the core of such knowledge, does it instead receive information about that knowledge from other brain region(s) that modulate its activation, or are the two completely independent? Moving from the detection of conflict by the ACC to the strengthening of control by the PFC, does such strengthening reflect a willful, conscious cognitive act, or is perhaps the order of causality the opposite, with the engagement of PFC giving rise to the "illusion" (Wegner, 2002) of, say, deciding to pay more attention to a given stimulus feature?

Here we will use the term *consciousness* to refer exclusively to the content of conscious representations. As articulated in more detail elsewhere, we take consciousness to be the result of a global constraint satisfaction process in which the winning neuronal coalition determines both accessibility and phenomenal experience (Maia and Cleeremans, 2005). We will center our discussion on whether conscious representations of current events, goals, and contexts are needed for conflict resolution and its contextual adaptation. We will further assume that these conscious representations, in contrast with long-term knowledge that is embedded in synaptic weights, rely on more transient, active representations encoded in the firing patterns of neurons. These active representations, unlike weight-based knowledge, can be accessible to other systems and are thought to be necessary, though not sufficient, for conscious awareness (Maia and Cleeremans, 2005). Even when different active representations originate in the same neuronal ensemble, the *quality* of the representations—i.e., their strength, duration, stability, distinctiveness, etc.,—might render only some of these representations accessible to consciousness. Some brain regions may potentially contribute less or not at all to conscious experience (Godwin et al., in press), so in those regions, even high-quality representations might not lead to conscious awareness. For instance, converging evidence suggests that while perceptual information in the ventral visual stream can become conscious (Doesburg et al., 2009), perceptual representations in the dorsal stream for visuomotor action may not be accessible to consciousness (Goodale and Milner, 1992, 2005). The regions involved in conflict monitoring and cognitive control, however, seem particularly likely to be implicated in conscious awareness (Morsella, 2005).

The core of our hypothesis is that the same types of representations in the same brain regions may give rise to either conscious or unconscious knowledge, depending on the quality of the representation—an idea that is consistent with a variety of lines of evidence, old (Kinsbourne, 1988) and new (Maia and Cleeremans, 2005). Such an effect may be direct, with high-quality representations becoming conscious *per se*, or it may be due to the fact that high-quality representations will have a higher probability of entering the "global workspace" (Baars, 1988; Dehaene et al., 2003) or winning the global constraint-satisfaction competition (Maia and Cleeremans, 2005). Even weak (and therefore unconscious) representations, however, can be causally efficacious in changing neuronal processing downstream (Cleeremans, 2004). Thus, we should not be surprised if unconscious processing—elicited, for example, by the subliminal presentation of stimuli (which simply elicits weaker representations)—produces effects similar to, but weaker than, supraliminal presentation of the same stimuli. This overarching theoretical perspective about the nature of conscious versus unconscious processing also allows us to cast our original questions in even more mechanistic terms, by asking whether active representations of a special quality are required for controlled processes and, if so, which specific control mechanisms require these special representations.

SUBLIMINAL-PRIMING STUDIES OF THE CAPABILITY OF UNCONSCIOUS PROCESSES TO INFLUENCE COGNITIVE CONTROL

Subliminal-priming studies (also known as masked-priming studies) have been used to assess whether unconscious processes affect a variety of cognitive, affective, and behavioral processes

(Eimer and Schlaghecken, 2003; van den Bussche et al., 2009). In these studies, stimuli are presented very briefly before being masked by another stimulus, so that the initial stimulus remains outside of awareness. Whether this manipulation does indeed render perception of the initial stimulus fully unconscious is not always uncontroversial—for example, at least some of these studies might be underpowered to detect above-chance discrimination of masked primes and thus wrongly assume unconscious perception of those primes (Szczepanowski and Pessoa, 2007). Nonetheless, the subliminal-priming approach is often assumed to indeed make perception of the initial stimulus (the prime) unconscious. For this reason, this approach has been used in conflict tasks to assess whether unconscious processes can affect cognitive control. Using masked and unmasked primes, an early study found that only consciously perceived conflict triggered conflict adaptation (Kunde, 2003). This result was interpreted as proof that only conscious information is used to adjust control. Later reports, however, seem directly at odds with this interpretation. Recent work has shown that both "unconscious errors"—defined as Go trials that followed a masked No-Go cue, but in which participants executed a response—and unconsciously primed conflict induce subsequent adjustments in behavior (Cohen et al., 2009; van Gaal et al., 2010). In particular, even conflict stimuli that are presented subliminally can induce conflict adaptation. These and other findings suggest instead that unconscious processing of information has many complex features that were once thought to be unique to its conscious counterpart (Wokke et al., 2011). Thus, unconscious processing of information seemingly can lead to adjustments in cognitive control. These findings, along with others similarly demonstrating that unconscious processes have many of the characteristics traditionally associated with conscious processes, are fully consistent with our view that the same brain regions can perform the same set of processes when stimulated subliminally and when stimulated supraliminally, with the main difference being the quality and strength of the resulting representations and processing. Further support for our view comes from the finding that the magnitude of the conflict-adaptation effect varies with the masking strength of the conflict-inducing prime: conflict adaptation following conscious primes is considerably greater than conflict adaptation following unconscious primes (van Gaal et al., 2010). In our view, this occurs simply because the subliminal presentation of stimuli does not have sufficient duration to elicit strong and durable neuronal firing, whereas the supraliminal presentation does.

Other studies have exploited both positive and negative effects in subliminal priming. While masked primes initially activate responses associated with the prime, thereby facilitating responses to targets that are compatible with it, at longer delays between prime and target this response facilitation turns into an inhibition (Eimer and Schlaghecken, 1998). A recent study used subliminal presentation of arrow primes (corresponding or non-corresponding with the target arrow) and measured the effect of long and short prime-target intervals on the response to a target arrow flanked by other arrows (congruent or incongruent flankers; Boy et al., 2010). The study showed that prime-induced inhibition at long intervals differentially affected responses to the current target depending on whether the target's flankers were congruent or incongruent with it. When the prime differed from the target, there was almost no additional cost for responses to incongruent as compared with congruent trials. Because subliminal priming interacted with current-trial congruence but not with conflict adaptation (i.e., the effect of unconscious inhibition was the same on incongruent trials preceded by an incongruent trial and on incongruent trials preceded by a congruent trial), the authors argued that unconscious inhibition might separate two types of control processes: a responsive (post-stimulus) control, related to conflict resolution, which might share motor mechanisms with unconscious processes, and a preparatory (pre-stimulus) control linked to conflict adaptation and which is impervious to unconscious inhibition. Although this distinction is appealing, an alternative account of these results is that unconscious inhibition does not affect either pre- or post-stimulus control. The putative effect on post-stimulus control—the above-mentioned finding that unconscious inhibition nearly abolished the extra cost for incongruent as compared to congruent trials—can in fact be given a simple explanation: at long intervals, primes that differ from the target inhibit the response tendency to the non-target direction, and therefore flankers that signal that direction have a weaker effect. Thus, there is reduced conflict when an incongruent trial is presented after such primes, and the response to the target becomes easier. Conversely, at short intervals, primes aligned with the target may facilitate reaction times in a nonspecific manner without weakening the effect of flankers, and thus, without reducing conflict. Regardless of the interpretation, since primes in this study were always presented unconsciously and flankers were presented consciously, these results provide additional support for our view that both conscious and unconscious stimulation of response tendencies engage overlapping brain regions and therefore interact with each other.

In summary, putting aside potential sensitivity issues in establishing the chance-level discrimination of masked primes necessary to assume unconscious processing (Szczepanowski and Pessoa, 2007), the subliminal-priming studies reviewed here provide strongly suggestive evidence that information that is unconsciously processed can induce certain events (e.g., conflict or error) that in turn engage control mechanisms.

ALTERNATIVE APPROACHES TO STUDY UNCONSCIOUS INFLUENCES ON COGNITIVE CONTROL

Under our suggestion that conscious and unconscious processes might share common mechanisms and differ mostly in terms of representation quality, unconscious processes would indeed be expected to influence control mechanisms, like their conscious counterparts do (Suhler and Churchland, 2009). Future studies should seek to elucidate whether the quality of representations and the conscious experiences associated with them have an influence on control, and if so, on which components of control. Our prediction is that their influence on control will not be qualitatively different but will be quantitatively stronger than that of unconscious processes, simply because stronger representations—potentially further amplified when they enter consciousness's "global workspace" (Baars, 1988; Dehaene et al.,

2003) or become part of the attractor state that solves the global constraint-satisfaction problem (Maia and Cleeremans, 2005)—have greater causal efficacy. We suggest that a sensitive assessment of the conscious knowledge that participants are able to report during a standard conflict task, in parallel with behavioral and imaging measures, would help tackle these issues. Here, we delineate this multimodal approach.

CONSCIOUSNESS AND THE SUBCOMPONENTS OF COGNITIVE CONTROL

As mentioned earlier, influential models of cognitive control have successfully accounted for behavioral effects in conflict tasks by incorporating several interacting neural components. In particular, the conflict-monitoring model accounts for conflict adaptation via a projection from a conflict-monitoring unit to a control unit, thereby allowing the occurrence of conflict on incongruent trials to trigger adjustments in control that improve performance on subsequent trials (Botvinick et al., 2001). The conflict-monitoring unit and the control unit are hypothesized to map onto the dorsal anterior cingulate cortex (dACC) and the dorsolateral prefrontal cortex (DLPFC), respectively. Thus, the model predicts that dACC conflict-related activity on the current trial predicts both greater DLPFC activity and greater adjustments in behavior on the subsequent trial—a prediction that has been confirmed empirically (Kerns et al., 2004). Research in nonhuman primates has added to this picture of how subcomponents of cognitive control interact. In particular, neuronal recordings in behaving monkeys have demonstrated that activity during inter-stimulus intervals in a population of neurons in the principal sulcus represents the previous trial's conflict (Mansouri et al., 2007). Furthermore, lesions to this region impair behavioral adjustments following conflict. These findings led to an extension of the conflict-monitoring model that posits that a mnemonic system encoding a representation of previous conflict (before the presentation of the following stimulus) is responsible for adjustments in behavior in the subsequent trial (Mansouri et al., 2009).

Using functional magnetic resonance imaging (fMRI), we recently identified a neural system, comprising the rostral dorsomedial prefrontal cortex (DMPFC) and portions of the DLPFC, that encodes the history of previously experienced conflict during inter-stimulus intervals in humans (Horga et al., 2011). We also demonstrated that this system reflects not only conflict in the immediately preceding trial but also the longer history of conflict in several preceding trials. This system interacted with a second system that was engaged by conflict in the current trial, an interaction that predicted trial-to-trial behavioral adjustments prompted by conflict (i.e., adjustments in the response to the current conflict trial relative to the response to the preceding conflict trial). In our study, inter-stimulus activation in the DMPFC-DLPFC had control-like features: it tracked conflict history and subsequently modulated other brain regions in a top-down manner. Unfortunately, this study was not designed to evaluate the degree to which conscious knowledge of previous conflict history was related to the activation of this control system or to the behavioral adjustments that ensued.

We interpreted the information encoded in the inter-stimulus DMPFC-DLPFC activation as either a memory trace of past conflict or a strategic expectancy. This distinction between a *reactive* memory process that is passively activated by conflict and a *proactive* process that anticipates the occurrence of a certain stimulus type and prepares an optimal action strategy accordingly, respectively, could potentially be important to understand the mechanisms of cognitive control. One way to parse out a purely mnemonic versus an expectancy account is to evaluate whether inter-stimulus activation in the DMPFC-DLPFC system can predict subsequent strategies, specifically certain oculomotor strategies that would only be beneficial if a stimulus of the expected type (e.g., incongruent) appears. Thus, monitoring a strategy such as the focusing of spatial attention—relevant to the resolution of conflict in spatial conflict tasks (Botvinick et al., 2001)—could be a viable way to determine if conflict is expected (whether such expectation is conscious or unconscious). That is, if inter-stimulus activation in the DMPFC-DLPFC system—measured with hemodynamic or electrophysiological imaging—predicted the spatial focusing of attention on the following trial, then this activation would be consistent with an expectancy account. This finding would be particularly compelling if such activation influenced oculomotor strategy, as measured with eye tracking, before an individual has enough time to process the stimulus (and potentially re-adjust the strategy after stimulus presentation), and most importantly, if the oculomotor strategy were specifically beneficial for responding to conflict trials but impaired performance on non-conflict trials.

CONSCIOUS KNOWLEDGE AND CONFLICT ADAPTATION

The potential role of consciousness in conflict adaptation could be examined by inquiring about participants' knowledge of their past conflict history and their use of strategy at specific time periods during a standard conflict task (**Figure 1**), and determining the extent to which such knowledge mediates behavioral adaptations. The inter-stimulus interval, for the reasons presented above, may be an appropriate time period for these inquiries. To avoid common failures in reporting conscious knowledge when open-ended questions are used, close-ended questions would be preferred (Maia and McClelland, 2004). The questionnaire should focus on the subcomponents of control that underlie conflict adaptation. At least two aspects of the control mechanism underlying conflict adaptation seem certain: it depends on prior conflict and its engagement benefits performance, i.e., once the control mechanism is engaged it contributes to improve subsequent conflict resolution. Consequently, the questionnaire should target participants' knowledge about the type of stimuli presented on preceding trials and their conscious expectations concerning the upcoming stimulus. Participants may possibly expect repetitions or alternations of certain stimulus types given the preceding sequence, even if stimuli are arranged in a random series (Huettel et al., 2002). The second goal of these inquiries would deal with specific cognitive or behavioral strategies that the individual might deploy in anticipation of the upcoming trial (e.g., focusing spatial attention on a specific region of the screen, preparing an "if-then" strategy, etc.). Lastly, subjective but

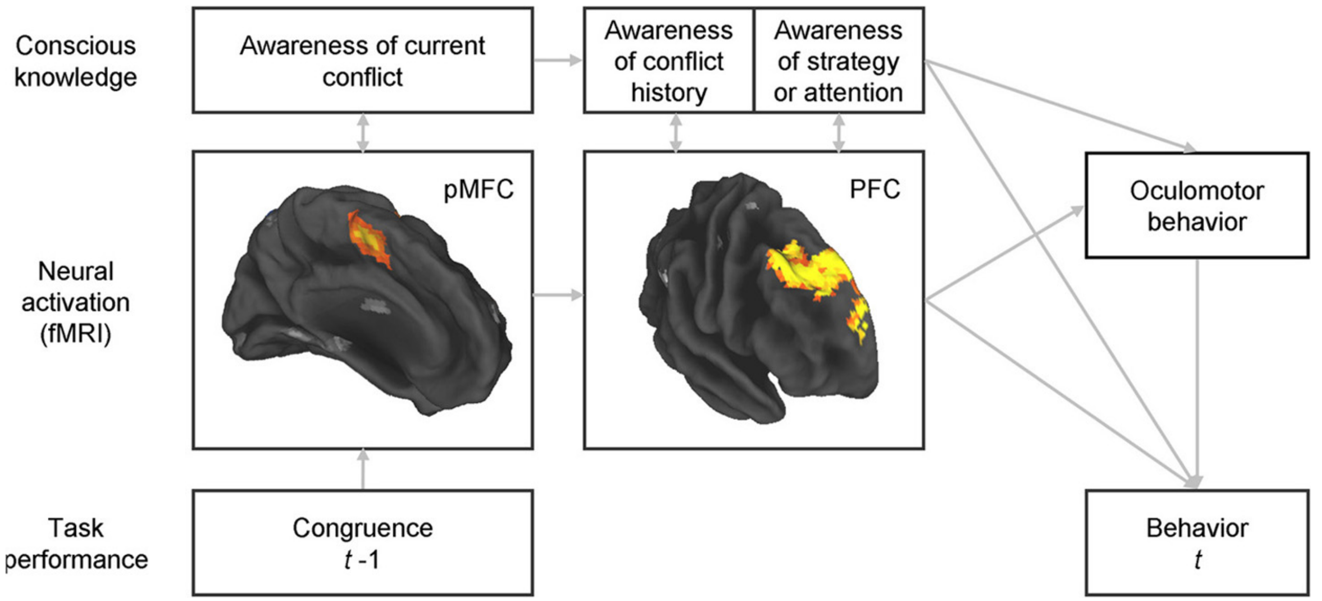

FIGURE 1 | Integrated assessment of the neural bases of conflict adaptation, potential strategic changes in the allocation of spatial attention, and adaptive changes in behavior, together with assessment of the accompanying conscious knowledge and of whether such knowledge plays a role in strategic changes in spatial attention or in performance adjustments. Simultaneous, multimodal assessment of brain activity, oculomotor behavior, choice and reaction-time behavior, and conscious knowledge would permit an understanding of the inter-relations between all of these variables. Some questions of particular interest would include: (1) whether awareness of each of the components of control is associated with greater activity in the corresponding brain regions (as predicted by our view on the nature of consciousness); (2) whether adjustments in oculomotor behavior that potentially reflect an expectancy of a certain type of stimulus are associated with conscious knowledge of such expectancy and of its effect on the allocation of spatial attention; and (3) whether behavioral adjustments (of oculomotor behavior or of choice and reaction times) are fully mediated by conscious knowledge or whether instead they can be adaptively influenced by neural activity in the PFC without accompanying conscious knowledge (as predicted by our hypothesis that neural activity in these circuits can be causally efficacious even it is not accompanied by conscious knowledge). pMFC, posterior medial frontal cortex (encompassing the dorsal anterior cingulate cortex and the pre-supplementary motor area); PFC, prefrontal cortex (specifically, rostral dorsomedial, and dorsolateral prefrontal cortex).

non-specific sensations such as arousal or attention should also be assessed, as participants might not explicitly know, for example, the history of conflict in the recent trials but nonetheless have a subjective sense that they need to pay, or are paying, more attention following conflict trials.

BRAIN-KNOWLEDGE-BEHAVIOR ANALYSES

A multimodal approach that includes recordings of neural activity, assessment of conscious knowledge, and behavioral measurements should be used to permit the assessment of the relations between these three variables. Our perspective that conscious and unconscious knowledge may differ mostly in the intensity and duration of neuronal firing predicts that greater neuronal activation measured, for example, with fMRI, should correlate with knowledge that is more conscious. In addition, greater activation should also, naturally, have a greater effect on behavioral adjustments. Thus, to some extent, we expect neuronal activation, conscious knowledge, and behavioral adjustments to be substantially correlated. However, we suggest that even activation that remains below the threshold required to enter consciousness can still be causally efficacious; thus, we predict that behavioral adjustments can occur even in the absence of conscious knowledge. Using path analysis, we recently showed that greater activity in the aforementioned DMPFC-DLPFC system during inter-trial intervals predicted greater behavioral adjustment to conflict on a trial-by-trial basis (Horga et al., 2011). With the measure of conscious knowledge, we could also test whether the effects of activation strength on behavior are mediated by conscious knowledge (**Figure 1**). The addition of eye tracking to this design, if specific oculomotor behaviors were linked to conflict adaptation, could further unravel the relationships between neural activation, strategic expectancies (reflected in oculomotor behavior), adaptive improvements in performance, and potential conscious knowledge about the strategic expectancies and their influence on behavior. In summary, this multimodal approach would allow us to assess whether, for purposes of conflict adaptation, conscious experiences are epiphenomenal or whether instead they play a central role in mediating the relationship between activity in the regions that have previously been implicated in conflict adaptation and adaptive control of behavior.

CONCLUDING REMARKS

Subliminal-priming paradigms have thus far been the method of choice for studying the role of unconscious processing in cognitive control. Despite some early contradictory findings, overall these studies suggest that unconsciously triggered conflict can induce adjustments in control mechanisms. These findings add to others that similarly demonstrate that unconscious processes possess several advanced characteristics (e.g., flexibility) that have traditionally been associated with conscious processes (Wokke et al., 2011). The dichotomy between higher-order control mechanisms that are conscious versus less complex, reflective mechanisms that are unconscious—each of which with its own separate neural substrates and processes—therefore, now seems less appealing than it once did. As an alternative to this idea, we have suggested a more graded view, in which conscious and unconscious processes might rely on the same neural substrates and perform the same processing, differing mostly on the quality of the representation. We have shown that this perspective seamlessly explains the bulk of the literature on unconscious influences in cognitive control.

One limitation of the subliminal-priming approach is that it seeks only to determine whether processes initiated by a subliminally presented prime affect cognitive control. Such an approach is, therefore, uninformative about the potential involvement of conscious versus unconscious processing under more standard task conditions (in which the stimuli themselves are presented supraliminally, but their effect on behavioral adjustments could be mediated by conscious or unconscious processing). We, therefore, proposed a complementary approach that uses standard task conditions but adds a questionnaire to assess participants' conscious knowledge. We indicated how a multi-modal approach could be used to understand the relation between activation in cognitive control areas, conscious knowledge, and behavioral adjustments—including assessing whether conscious knowledge mediates the effect of activation in cognitive control areas on behavioral adjustments. Overall, we hope that both the theoretical perspective that we articulated in this article and our suggestions about a complementary empirical approach to these issues could be of value in guiding future thinking and experimentation in this area.

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The pervasive nature of unconscious social information processing in executive control

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Humans not only have impressive executive abilities, but we are also fundamentally social creatures. In the cognitive neuroscience literature, it has long been assumed that executive control mechanisms, which play a critical role in guiding goal-directed behavior, operate on consciously processed information. Although more recent evidence suggests that unconsciously processed information can also influence executive control, most of this literature has focused on visual masked priming paradigms. However, the social psychological literature has demonstrated that unconscious influences are pervasive, and social information can unintentionally influence a wide variety of behaviors, including some that are likely to require executive abilities. For example, social information can unconsciously influence attention processes, such that simply instructing participants to describe a previous situation in which they had power over someone or someone else had power over them has been shown to unconsciously influence their attentional focus abilities, a key aspect of executive control. In the current review, we consider behavioral and neural findings from a variety of paradigms, including priming of goals and social hierarchical roles, as well as interpersonal interactions, in order to highlight the pervasive nature of social influences on executive control. These findings suggest that social information can play a critical role in executive control, and that this influence often occurs in an unconscious fashion. We conclude by suggesting further avenues of research for investigation of the interplay between social factors and executive control.

Keywords: executive control, self-regulation, prefrontal cortex, visual masked priming paradigm, social priming, social power, behavioral mimicry, impression management

INTRODUCTION

Our everyday lives require a tremendous amount of deliberate behavioral regulation, including planning actions, inhibiting response tendencies, and updating goals in light of new information. These processes, known collectively as executive control, are thought to rely on the prefrontal cortex (PFC) (see Miller and Cohen, 2001 for a review) and to typically operate on consciously processed information. The definition of "consciousness" continues to serve as the topic of debate. Nonetheless, many theories of executive control view consciously processed information as that information within participants' awareness that can trigger intentional and deliberate behavioral regulation (see Jack and Shallice, 2001; Hommel, 2007). Although several studies have shown that unconsciously processed information, or information processed outside of participants' awareness, can influence a wide variety of behaviors, including semantic (e.g., Markus and Spitzer, 2000) and emotional (e.g., Whalen et al., 1998) processing, many view executive control as a higher-order function that is triggered only under conditions involving conscious awareness of conflict (Atkinson and Shiffrin, 1968; Norman and Shallice, 1986; Umilta, 1988; Dehaene and Naccache, 2001; Jack and Shallice, 2001). Additionally, the PFC has been suggested to serve as a neural correlate of consciousness, further underscoring the tight link in the literature between this brain region, executive control, and consciousness (Dehaene and Naccache, 2001; Rees et al., 2002; Crick and Koch, 2003; Eimer and Schlaghecken, 2003). Indeed, some have viewed the very idea of unconscious executive control as an unlikely phenomenon (e.g., Dehaene and Naccache, 2001; Jack and Shallice, 2001). However, more recent evidence suggests that not only is unconscious executive control a plausible concept, but it is also a commonly occurring phenomenon in our everyday lives (Hommel, 2007; Suhler and Churchland, 2009).

Similar to the debate surrounding the definition of "consciousness," there is much controversy regarding the meaning of the term "unconscious" (see Pessoa, 2005; Bargh and Morsella, 2008). Whereas the cognitive neuroscience literature has largely focused on unconscious information processing in terms of *stimuli* outside of awareness (i.e., subliminal stimuli), the social psychology literature has emphasized *mental processes* that function outside of awareness (Bargh and Morsella, 2008; see also Nisbett and Wilson, 1977). As noted by Bargh and Morsella (2008), subliminal stimuli are weak and unnatural, thus making it difficult to assess the true scope of unconscious processing using these types of stimuli. In contrast, the social psychology literature has studied unconscious processing through investigation of how stimuli within awareness (i.e., supraliminal stimuli) can result in unconscious influences on behavior through unintentional activation of mental processes that operate outside of awareness. The results from these studies suggest that unconscious processes have a surprisingly powerful influence on our behavior (Bargh and Morsella, 2008).

In the current review, we view unconscious executive control through the social psychological lens in order to highlight how social information can lead to unintentional triggering and engagement of executive control. First, we briefly review evidence from studies in the cognitive neuroscience literature that have used visual masked priming paradigms featuring subliminally presented visual stimuli to investigate unconscious visual information processing in executive control. We then highlight unconscious influences on executive control in the social domain, revealed via paradigms involving social priming and social interactions. It is important to note that there are both masked (i.e., subliminal) and unmasked (i.e., supraliminal) types of cognitive (e.g., visual) and social priming paradigms. For the purposes of the current review, we have focused on masked cognitive (visual) priming paradigms and unmasked social priming paradigms, as these methods have yielded several interesting findings regarding unconscious influences on executive control. Although several social psychology studies have demonstrated ways in which social factors can unconsciously have an impact on executive control, these findings have not received as much attention in the cognitive neuroscience literature. We review these findings with the aim of demonstrating the pervasive nature of unconscious social influences on executive control, as well as suggesting the need for further exploration of these influences at both behavioral and neural levels.

VISUAL MASKED PRIMING PARADIGM

Several recent studies used a visual masked priming paradigm to show that unconsciously processed visual information can trigger executive control, reflected through behavioral interference effects as well as activation of PFC. This paradigm involves presentation of a prime (e.g., a small shape) followed by a stimulus (e.g., a large hollow shape) for which participants are asked to make a response of some sort (e.g., press a button). One method of masking the prime, known as metacontrast masking, involves using a prime that has overlapping contours with the stimulus and results in reduced visibility of the prime (see Lau and Passingham, 2007; van Gaal et al., 2008, 2010; for examples of this approach). The duration of the interval between the onsets of the prime and stimulus can be altered such that a long interval increases the visibility of the prime, whereas a short interval renders the prime consciously imperceptible to the participant. Typically, the prime is either congruent or incongruent with the consciously perceptible stimulus in order to assess whether the prime can induce conflict, even though it is below the level of conscious awareness. In order to ensure that participants cannot consciously detect the primes, participants typically perform a separate discrimination task, in which they are asked to report the identity of the masked prime, after the main experimental procedure.

Interestingly, studies employing visual masked priming paradigms have shown that unconsciously perceived information can trigger executive control in a variety of different ways. For example, Lau and Passingham (2007) had participants perform either a phonological or semantic task for a presented word depending on the identity of an instruction figure shown prior to the word. When presented with a square, participants had to make a phonological judgment on the word, and when presented with a diamond, participants had to make a semantic judgment. A masked prime was presented prior to the instruction figure that was either congruent or incongruent in identity to the instruction figure. Lau and Passingham (2007) found that incongruent masked visual primes led to establishment of the incorrect task-set, reflected by impaired behavioral performance as well as activation in neural regions associated with the incorrect task and in dorsolateral prefrontal cortex (DLPFC). These results suggest that unconsciously perceived information can influence executive control-related PFC activity, thereby suggesting that consciousness is not a prerequisite for the activation of this neural region. Furthermore, as Lau and Passingham (2007) note, the establishment of task-sets and goals is a critical component of executive control (see also Miller and Cohen, 2001), which indicates that unconsciously perceived information can have a significant impact on higher-order behavior.

In addition to establishment of task-sets, studies employing visual masked priming paradigms have demonstrated that unconsciously perceived visual information can trigger inhibitory control mechanisms and related PFC activity (van Gaal et al., 2008, 2010). For example, van Gaal et al. (2010) used a visual masked priming version of a Go/No-Go task, in which participants were instructed to press a button in response to a Go stimulus (a white annulus), but to inhibit that response if a No-Go prime (a white square) appeared before the Go stimulus. The authors found that consciously imperceptible masked No-Go primes were able to increase reaction times, suggesting triggering of inhibitory control mechanisms that resulted in a slow-down in responding, compared to masked Go primes (a white diamond). Furthermore, masked No-Go trials were associated with activity in brain regions associated with inhibitory control, namely inferior frontal cortex and the pre-supplementary motor area. Thus, unconsciously perceived information appears to be able to trigger different types of executive control mechanisms and their PFC neural substrate (see also Verbruggen and Logan, 2009; Wokke et al., 2011).

SOCIAL INFLUENCES ON EXECUTIVE CONTROL

Although the studies discussed above provide compelling evidence for unconscious triggering of executive control, they have almost exclusively used visual masked priming paradigms to demonstrate these effects. In order to obtain a more comprehensive view of the relationship between unconscious processing and executive control, it is important to investigate other domains that can inform our understanding of this topic. The social psychological literature has reported unconscious influences of the social environment on a myriad of complex behaviors, including trait-consistent behaviors (e.g., walking more slowly after presentation of words related to the elderly stereotype; Bargh et al., 1996), goal-pursuit (e.g., Aarts et al., 2004), and helping behavior (e.g., Garcia et al., 2002; see Ferguson and Bargh, 2004 for a review). However, the question remains as to whether social information can trigger executive control in an unconscious fashion. In the current review, we contend that not only is this a possible phenomenon, but that unconscious social influences on executive control occur in a pervasive manner in our everyday lives.

Before we turn to the evidence supporting this conclusion, it is useful to consider two questions. First, why might social information trigger executive control? And second, why might this influence occur in an unconscious fashion? Turning to the first question, the frontal lobes of the primate brain have been suggested to support two impressive domains of human cognition: executive control as well as social cognition. The frontal lobes are thought to serve as a key neural substrate for social cognition due to the need for behavioral regulation in a manner that is sensitive to the current social context (see Adolphs, 2001, 2010 for reviews). Furthermore, it has been suggested that the evolution of the primate brain, particularly the expansion of the frontal lobes, occurred in response to the social complexity of our environments (Humphrey, 1976; Dunbar, 2003; Dunbar and Shultz, 2007). In light of the tight link between executive control and social cognition, it is perhaps not too surprising that social information can serve as a trigger of executive control. However, can this influence occur without our awareness? Humans' conscious executive control resources, although impressive in the ability to support behavior in both a flexible and goal-directed fashion, are thought to be limited in nature. Thus, the ability for social information to trigger executive control without our awareness may allow us to automatically and efficiently suppress socially inappropriate response tendencies through practice over time, thereby greasing the cogs of social interaction (Suhler and Churchland, 2009; van Gaal et al., 2010).

Given the ubiquitous nature of social influences in our environment, there are several ways in which social information can trigger executive control without our awareness. In the current review, we consider behavioral and neural evidence from paradigms involving social priming of task-sets and hierarchical roles, as well as interpersonal interactions, and their unconscious influences on executive control. We focus on evidence from two types of techniques (see Bargh and Chartrand, 2000; Smith and Galinsky, 2010 for reviews of these methods). First, we focus on priming techniques involving the unconscious activation of participants' social knowledge and subsequent carry-over effects to executive control tasks. Next, we focus on the use of social interactions as a means of activating social knowledge and unconscious carry-over effects affecting executive control in new situations.

At which levels of processing do these unconscious social influences operate? In some cases discussed in this review, social knowledge is activated unconsciously and participants also remain unaware that this information influences executive control. In other cases, processing of social information and triggering of executive control in a social situation may be conscious, but participants are not aware that this experience has an impact on executive control in a seemingly unrelated situation. Thus, although the level at which unconscious influences operate can vary across studies, what the reviewed studies have in common is that they involve unconscious carry-over effects of social information processing on executive control.

SOCIAL PRIMING

The social priming paradigm serves as a commonly used technique in the social psychology literature and involves the use of a manipulation that is designed to prime, or activates, social knowledge (e.g., a trait). The priming task can take one of many different forms, such as filling out a questionnaire in which participants are asked to provide their thoughts regarding a particular social concept, solving a scrambled sentences task where certain keywords are embedded within the sentence, or completing a lexical decision task where keywords serve as a subset of the word stimuli (see Bargh and Chartrand, 2000). Participants are then asked to complete an ostensibly unrelated task, which in actuality, serves as the dependent measure. The social priming technique assesses the impact of implicit activation of social knowledge on judgments and behaviors to the extent that participants are unaware of the influence of the priming task on the main dependent measure (Bargh, 1992; Bargh and Chartrand, 2000). The level of awareness can vary depending on the type of priming manipulation. For example, in the case of social conceptual priming, participants complete a task (e.g., scrambled sentences task) involving words (e.g., "lonely," "forgetful," "wrinkle") related to a particular social concept (e.g., the elderly stereotype; see Bargh et al., 1996). In this type of priming task, participants are aware of the words and sentences. However, they are typically unaware of the activation of social knowledge concepts as well as subsequent effects on a seemingly unrelated task. In the case of social mindset priming, participants complete a task (e.g., filling out a questionnaire asking them to reflect on a time when they had power over someone else) that explicitly asks them to think about a social concept (e.g., social power; Galinsky et al., 2003). In this type of priming task, participants are aware of the activation of social knowledge; however, they tend to remain unaware that this activation persists to influence performance on a seemingly unrelated task (see Bargh and Chartrand, 2000; Smith and Galinsky, 2010 for reviews).

Social priming techniques share much in common with visual masked priming paradigms in that both types of methods aim to uncover unconscious influences on cognitive processes. However, there are also important differences which should be noted. In the case of visual masked priming paradigms, participants are both unaware of having perceived the masked prime as well as its subsequent effects on performance. In contrast, conceptual and mindset forms of social priming often, although not necessarily, involve conscious perception of the prime; however, the influence of this knowledge on subsequent performance tends to operate in an unconscious fashion. In order to ensure the success of the experimenters' cover story that the social priming and dependent measure tasks were unrelated, participants are extensively debriefed to assess their level of awareness at the conclusion of the experiment. Although some have criticized this method of assessing unconscious processing of social information (Orne, 1962; see Ferguson and Bargh, 2004 for a review), the social priming technique has been widely accepted as a means of assessing the unconscious influences of social information on behavior.

SOCIAL PRIMING OF TASK-SETS AND GOALS

Social priming techniques have been used to demonstrate how the activation of social knowledge can unconsciously affect executive control. In a recent study, Goldfarb et al. (2011) had participants first perform two blocks of the Stroop task (Stroop, 1935), a classic measure of executive control that assesses participants' abilities to resolve conflict between competing incompatible responses. In this task, participants must name the ink color of a presented stimulus whose meaning is either congruent (e.g., "red" presented in red ink), incongruent ("red" presented in blue ink), or neutral (e.g., "xxxx" presented in red ink), with respect to the ink color. Participants then completed an ostensibly unrelated questionnaire, which served as the social priming manipulation. In this questionnaire, participants were asked to imagine a typical day for a severely dyslexic individual as a means of priming a "do not read" task-set. Following the priming manipulation, participants performed two additional blocks of the Stroop task. Interestingly, participants failed to show a significant Stroop effect (i.e., difference in reaction times for incongruent and congruent trials) only for the block immediately following the dyslexia priming manipulation. In a control social priming condition, participants were asked to imagine a typical day for an individual with severe mathematical difficulty, and no reduction in the Stroop effect was found for this condition. Furthermore, debriefing indicated that participants were not aware of the relationship between the social priming manipulation and the Stroop task. This study suggests that the dyslexia social priming manipulation temporarily activated a task-set and subsequent behavior in line with this task-set in the absence of participants' awareness. Thus, this study serves as a social analog to Lau and Passingham (2007) in demonstrating that social priming, similar to the visual masked priming paradigm, can establish a task-set in an unconscious fashion.

These results are in line with several previous studies demonstrating that similar to task-sets, goals can be activated in an automatic fashion, such that perceiving another individual pursuing a particular goal can lead to activation of the same goal within the perceiver (e.g., Aarts et al., 2004). This phenomenon of "goal contagion" suggests that the social environment can exert a powerful influence on our behavior, in ways that are often beyond our awareness. Goals often involve self-regulation of one's own thoughts, actions, and emotions. For example, self-regulatory abilities allow us to resist the temptation of a piece of cake when one's goal involves dieting, and enable us to study for an exam rather than attend a party when one's goal involves doing well in a course (Ackerman et al., 2009). Self-regulation is thought to rely on executive control resources, such as inhibitory control (see Baumeister, 1998; Barkley, 2001).

The examples of self-regulation provided above seem to involve difficult and deliberate choices that are conscious in nature. How might social information trigger self-regulation in an unconscious fashion? Although the bulk of research on self-regulation has focused on intra-personal self-regulatory processes, more recent studies suggest that inter-personal social factors can influence the success of self-regulation, and that this influence can occur in an unconscious fashion (see Fitzsimons and Finkel, 2010 for a review).

For example, recent work has demonstrated that social priming manipulations can influence self-regulation. Ackerman et al. (2009) had participants read either a story about a hungry waiter/waitress who had to exercise self-control by not eating the delicious food being served at the restaurant where he/she worked, or a story about a waiter/waitress who was not hungry and did not have to exercise self-control. Some participants were instructed to adopt the perspective of the waiter/waitress, whereas others were simply instructed to read the story. Participants then performed seemingly unrelated tasks requiring self-regulation in different domains, including indicating their willingness to spend money on luxury goods as well as persistence in a lexical generation task. Interestingly, the authors found that participants who adopted the perspective of the hungry waiter/waitress demonstrated less self-control (e.g., less words generated in the lexical generation task), suggesting depletion of self-regulatory resources, compared to participants who adopted the perspective of the waiter/waitress who did not have to exercise self-control. In contrast, participants who merely read about the hungry waiter/waitress exercised greater self-control (e.g., more words generated in the lexical generation task), indicating a goal-contagion effect, compared to participants who read the story that did not involve self-control. These results suggest that the self-regulation of others can unconsciously influence our own self-regulatory abilities, and that the nature of this impact can depend on the extent to which we adopt the perspective of others. In sum, social information can unconsciously trigger executive control in the form of establishing task-sets and goals, as well as guiding behavior accordingly.

PRIMING OF SOCIAL HIERARCHIES AND POWER DYNAMICS

In addition to task-sets and goals, social priming methods have also been used to investigate the unconscious influence of social roles on behavior. In our everyday lives, we tend to serve a variety of social roles (e.g., teacher, student, parent, child, boss, employee, etc.) depending on our relationships with other people in our environments (Fiske, 1992). How do these roles guide our behavior? And more specifically, can these roles trigger executive control in the absence of our awareness? Below, we focus on social hierarchical roles and their unconscious influence on executive control.

Social hierarchies play an important role in our everyday lives and have an impact on how we interact with other people (Cummins, 2000). Those who have higher positions in social hierarchies tend to wield more power, in that they exert greater control over the behaviors of other people. These power dynamics tend to influence where we direct our social attention, such that individuals with less power tend to direct their attention to those who control their fates (Fiske, 1993; cf. Overbeck and Park, 2006). However, social power roles also have broader consequences on the processing of information and guidance of behaviors that are not explicitly social in nature. Indeed, power can be conceived of as a psychological construct that upon activation, results in broad downstream effects influencing how we think, feel, and behave across a variety of social and non-social contexts (Galinsky et al., 2003; Keltner et al., 2003; Smith and Galinsky, 2010). The psychological construct of power can be activated in either a conscious or unconscious fashion with similar effects on behavior (Galinsky et al., 2003). Smith and Galinsky (2010) noted that not only can power influence behavior unconsciously, but these unconscious influences also have far-reaching consequences in our daily lives. For example, individuals primed with high power roles tend to engage in more abstract thinking on both conceptual and perceptual tasks (Smith and Trope, 2006) and are also more likely to engage in action across a broad variety of contexts, including those unrelated to the possession of power (Galinsky et al., 2003).

A few recent studies have shown that social power roles can have an impact on executive control in the absence of participants' awareness. Guinote (2007) investigated the impact of social power roles on attentional control across a series of experiments. After completing a manipulation designed to prime either high-power or low-power social roles, such as describing a previous incident in which participants had power over others (high power) or others had power over them (low power), participants completed seemingly unrelated tasks targeting the ability to focus on task-relevant information in the presence of distracting task-irrelevant information. For example, in one of these tasks, participants were asked to indicate the orientation (i.e., upright or inverted) of presented objects by pressing either a left or right key on a keyboard. The images of objects also contained salient task-irrelevant information in the form of a handle on either the right or left side of the object. On compatible trials, there was a match between the correct button to be pressed and the side of the object on which the handle appeared, whereas incompatible trials featured a mismatch between these dimensions. As more powerful individuals depend less upon situational constraints and have more control over their environment, Guinote (2007) hypothesized that these people may be better able to allocate their attention to task-relevant information and ignore task-irrelevant information. In contrast, powerless individuals are more dependent upon externally defined constraints. Thus, they may need to simultaneously process multiple cues due to uncertainty regarding which cues are task-relevant or task-irrelevant. In support of these hypotheses, Guinote (2007) found that low power-primed individuals' reaction times were influenced by the compatibility of the handle position with the hand used to make the response, indicating that task-irrelevant information influenced their performance. In contrast, high power-primed individuals' reaction times did not differ between compatible and incompatible trials. These results suggest that high power-primed participants were better able to allocate attention to goal-relevant information compared to low power-primed participants.

Additional work has further explored the impact of social power roles on executive control by focusing on the effects of powerlessness on specific executive control mechanisms, including updating, inhibiting, and planning (Smith et al., 2008). Smith et al. (2008) primed social power roles through a variety of means, including assignment of participants to either superior or subordinate roles for a purported future interaction that never took place, a sentence-unscrambling task featuring words associated with either low or high power, and a writing task in which participants had to describe a situation in which they felt that they had high or low power. Across separate experiments, participants then completed executive control tasks targeting updating (n-back task), inhibition (Stroop task), or planning (Tower of Hanoi task). Smith et al. (2008) consistently found that low power-primed participants demonstrated poorer performance (i.e., higher error rates in the n-back task, higher error rates for incongruent trials in the Stroop task, greater number of moves for conflict trials in Tower of Hanoi task) compared to high power-primed participants for each specific executive control mechanism that was targeted.

In order to further target the source of executive impairments associated with low power, Smith et al. (2008) conducted an additional experiment in which participants performed one of two variants of the Stroop task. In one of these variants, participants were presented with a high proportion of congruent trials, where goal maintenance demands are high due to the ability to successfully perform the task by reading the word, thereby neglecting the goal to focus on the ink color, on the majority of trials. In the other variant, participants were presented with a high proportion of incongruent trials, thereby keeping goal maintenance demands low from trial to trial, but increasing inhibition demands. The authors found a difference in performance between high and low power-primed participants only for the Stroop task variant with a high proportion of congruent trials, with low power-primed participants demonstrating higher error rates on incongruent trials compared to high power-primed participants. Thus, the authors contend that low power-primed participants' poorer performance stemmed from goal neglect, or difficulty in maintaining a goal for a given task. Although participants in this study were randomly assigned to high or low power priming conditions, the authors contend that these findings have implications for social hierarchies within organizations. As those with low power must often rely on others for instructions or directions, they may have fewer opportunities to pursue their own goals. Smith et al. (2008) speculate that low power roles may further contribute to this disparity through impairment of the very cognitive processes necessary for goal maintenance and pursuit. Similar to Guinote (2007) findings, these results suggest that social power roles unconsciously influence executive control.

NEURAL CORRELATES OF SOCIAL POWER PRIMING

In addition to the behavioral evidence discussed above, neural evidence suggests that priming of social power roles can unconsciously trigger PFC activity that may reflect engagement of executive control mechanisms. For example, Boksem et al. (2009) demonstrated that during a priming task in which participants were asked to write about a previous situation where they had either high or low power, increased EEG activity in left (relative to right) PFC was associated with the high-power versus low-power priming task. Previous work has suggested that both high-power roles (e.g., Keltner et al., 2003) and increased left (relative to right) PFC activation (e.g., Sutton and Davidson, 1997) are associated with approach motivation. Thus, the authors speculate that high-power roles may engage PFC-mediated executive control mechanisms involved in goal-directed behavior and facilitation of approach tendencies. Although these findings indicate a link between social power roles and PFC activity, the extent to which this PFC activity reflects recruitment of executive control mechanisms remains speculative in nature. However, Boksem and colleagues have explored this issue further. Recent work by Boksem et al. (2011) suggests that low power social roles may not necessarily lead to a generalized deficit in executive control, but rather, may influence the types of executive control mechanisms that participants recruit. Boksem et al. (2011) found that participants who were assigned a lower status in an interactive time estimation task demonstrated a stronger medial frontal negativity, an event-related potential that serves as a measure of participants' evaluation and monitoring of their performance, compared to high-status individuals. As noted by the authors, these findings suggest that lower status individuals are more likely to engage in monitoring and adjustment of their performance, which stands in contrast to the work of Guinote (2007) and Smith et al. (2008). However, Boksem et al. (2011) suggest that rather than having poorer executive control, low power individuals may rely on a different executive control system that is more adaptive to their more unpredictable environments. Specifically, the authors propose that low-status individuals may rely on a reactive control system, which operates in a transient fashion and is triggered in response to a stimulus. In contrast, high-status individuals may rely on a proactive control system, which involves the active, sustained maintenance of task-relevant information (see also Braver et al., 2008).

Evidence from neuroimaging studies suggests the sensitivity of PFC to cues associated with social power roles. Marsh et al. (2009) had participants perform a gender discrimination task for photographs of male and female actors depicting high-status (e.g., low brow position) and low-status (e.g., high brow position) cues. Marsh et al. (2009) found increased activity in right ventrolateral prefrontal cortex (VLPFC) and left DLPFC associated with implicit processing of high-status versus low-status cues. Marsh et al. (2009) suggest that this activation may reflect the role of PFC in guiding behavior in an appropriate fashion given the current social context. Additionally, neuroimaging evidence suggests the sensitivity of PFC to social power roles, even when they are irrelevant to task performance. Zink et al. (2008) created an explicit social hierarchy in the context of a game situation, in which participants simultaneously played a game with one of two other simulated players, one of whom was superior in status to the participant and the other who was inferior in status. The game was non-competitive in nature such that status was irrelevant to the outcome of the game. Interestingly, the authors found greater DLPFC activity when participants viewed the picture of a superior versus inferior-status player, and this difference in DLPFC activity was not observed in a nonsocial version of the task where participants played with non-human computer players. The authors suggest that DLPFC plays a role in the processing of social hierarchical information.

In sum, results from EEG, ERP, and fMRI studies demonstrate that social power roles can trigger activity in DLPFC, even when those roles are not task-relevant. In light of the abundant evidence suggesting the critical role of DLPFC in supporting executive control, the studies discussed above indicate the sensitivity of this executive control-related neural region to social hierarchies. Together with the behavioral results discussed above, these studies suggest that social power roles have far-reaching consequences for our behavior, and that these influences often occur outside of our awareness. It is important to note that the majority of these studies have speculated rather than explicitly tested that observed PFC activity reflects engagement of executive control mechanisms. However, given that the PFC's role in social cognition has been suggested to consist of the engagement of executive control to regulate social behaviors (see Adolphs, 2001), these speculations do not seem unwarranted. Nonetheless, further investigation is clearly necessary in order to elucidate the specific contributions of PFC to social power dynamics.

SOCIAL INTERACTIONS

The studies reviewed thus far have demonstrated how the activation of social knowledge can have important downstream consequences for our abilities to use executive control in seemingly unrelated situations. These studies have tended to employ subtle priming manipulations, such as reading about other individuals or performing a simple scrambled sentences task. Although impressive in terms of their subtlety, one could argue that these types of manipulations do not truly capture the social nature of our environments.

As social creatures, we spend a great deal of time interacting with others. Can these social interactions affect executive control? And can this influence occur in an unconscious fashion? Below, we review evidence suggesting that social interactions can trigger executive control in surprising ways, and that this influence occurs without our awareness more often than we may think. The results of several studies indicate that not only the types of social interactions, but also the types of interaction partners, can unconsciously influence executive control. In particular, we consider how subtle aspects of our social interactions, such as interpersonal coordination and behavioral mimicry, as well as the gender and race of our interaction partners can trigger executive control in the absence of our awareness.

TYPES OF SOCIAL INTERACTIONS

High-maintenance social interactions

Our daily lives often involve working on tasks with other individuals. For example, we may work with others in order to design an experiment or write a paper at work, or cook a meal with friends at home. Although working with others can increase efficiency, sometimes social coordination is inefficient and taxing in nature. Recent work suggests that the nature of social interactions involving coordination can affect self-regulation, which as noted above, is thought to rely on executive control mechanisms. Due to the limited nature of self-regulatory resources, our deployment of these resources comes at a cost, such that executive control may be depleted for subsequent situations requiring the same resources (Muraven and Baumeister, 2000; Baumeister, 2002; cf. Job et al., 2010). Thus, the depletion of these resources due to an effortful social interaction can result in fewer resources available for subsequent situations, even those that are non-social in nature.

Under this hypothesis, recent work has investigated the impact of high-maintenance social interactions, which involve inefficient social coordination, on self-regulation. Finkel et al. (2006) had participants first engage in either a high- or low-maintenance interaction with a confederate in the context of a collaborative task. In high-maintenance interactions, confederates impeded social coordination (e.g., deliberately making errors when giving directions to the participant), whereas in low-maintenance interactions, confederates facilitated social coordination (e.g., making no errors when giving directions and remaining in sync with the participant). After the social interaction, participants performed ostensibly unrelated tasks designed to assess self-regulatory abilities, such as preference for easy versus challenging tasks, and performance on an anagram task and Graduate Record Examination questions. Across studies, the authors found that high-maintenance social interactions resulted in impaired self-regulation on subsequent unrelated tasks. Furthermore, this effect was not mediated by conscious awareness of the high-maintenance nature of the social interaction, which was assessed via participants' self-reports of subjectively experienced depletion, liking for their interaction partner, or mood. The authors suggest that this effect may stem from the depletion of self-regulatory resources during high-maintenance interactions, as individuals may need to resist the temptation to discontinue the interaction or respond in socially inappropriate ways. These results suggest that high-maintenance social interactions can deplete self-regulatory resources without our awareness, and that this impact extends to subsequent unrelated situations that also rely on self-regulatory abilities.

Behavioral mimicry

Behavioral mimicry serves as another example of an unconscious influence of social interactions on executive control. We tend to mimic the behaviors of others, such as imitation of others' physical gestures and mannerisms, and this can facilitate social interactions (Chartrand and Bargh, 1999; Chartrand and Dalton, 2009). Behavioral mimicry is thought to operate via implicit schemas activated in an automatic and context-dependent fashion (Bavelas et al., 1986; Bernieri, 1988; Chartrand and Bargh, 1999; Lakin et al., 2003). However, situations in which mimicry violates social norms disables the use of schemas, and as a result, social interactions proceed in a more effortful fashion.

Dalton et al. (2009) examined the cognitive consequences of violation of mimicry norms in a series of experiments, with a focus on the impact of behavioral mimicry on the availability of executive and self-regulatory resources (see also Finkel et al., 2006, Experiment 5). In one experiment, Dalton et al. (2009) investigated the impact of social power roles, in the context of social interactions, on executive control. As noted above, priming of social power roles can trigger executive control. Power dynamics also provide a set of social norms that tend to guide behavior in ways appropriate to one's social role. For example, those people in social roles associated with less power, such as workers, tend to mimic the behavior of those people in social roles associated with more power, such as leaders (Cheng and Chartrand, 2003). The extent to which these norms are followed can have downstream effects on executive control, and strikingly, these effects can occur in an unconscious fashion. Thus, going beyond the priming of power roles, power dynamics can unconsciously affect executive control in the context of social interactions with others.

Dalton et al. (2009) manipulated social roles by assigning some participants to be leaders for a future interaction which did not take place and was only mentioned as a means of manipulating social roles. Other participants were assigned to be workers, where a confederate played the complementary social role (e.g., a worker, if the participant had been designated as a leader). Participants and confederates then completed a joint photo description task, where the confederate either did or did not behaviorally mimic the participant. For the condition featuring behavioral mimicry, the confederate mimicked the postures, gestures, and mannerisms of the participant, including crossing arms and legs, as well as touching one's own face and hair. For the no-mimicry condition, the confederate remained behaviorally out of sync with the participant, such that there was a constant mismatch in physical behaviors between the confederate and participant throughout the joint task. The authors found that when behavioral mimicry violated social norms (i.e., the leader confederate behaviorally mimicked the worker participant, or the worker confederate did not behaviorally mimic the leader participant), participants demonstrated greater interference (i.e., larger difference in reaction times between incongruent and neutral trials) on a subsequent Stroop task. Furthermore, none of the debriefed participants indicated awareness of being mimicked during the photo description task, suggesting that the impact of behavioral mimicry on executive control occurred in an unconscious fashion. These results expand on the findings of Finkel et al. (2006) to demonstrate the powerful impact of inefficient or counter-normative social interactions on executive control, even in situations where participants are not aware of the high-maintenance nature of the social interaction.

IMPRESSION MANAGEMENT AND IDENTITY OF INTERACTION PARTNERS

Another important aspect of our everyday lives concerns how we present ourselves to others. Self-presentation (i.e., impression management) refers to the processes involved in managing the impression that one presents to others, and has important consequences for several aspects of our daily lives, including making friends, developing romantic relationships, getting a job, and acquiring other social and financial rewards or outcomes (Baumeister, 1982; Leary and Kowalski, 1990; Vohs et al., 2005). Importantly, impression management can differ depending on the social context and can also vary in terms of the level of awareness involved (see Baumeister, 1982; Schlenker and Weigold, 1992 for reviews). In familiar situations, such as talking with a good friend, we tend to rely on well-practiced behaviors that can proceed in an automatic, effortless fashion. However, in unfamiliar or novel situations, such talking to the president of the company where we work, we may have to rely on more effortful processing in order to effectively control our behaviors to be in line with the impression that we wish to convey.

Such effortful impression management has been suggested to rely on self-regulatory resources and to have important consequences for subsequent situations reliant on self-regulation (Vohs et al., 2005). In order to test this hypothesis, Vohs et al. (2005) conducted a series of experiments in which participants first engaged in effortful, counter-normative self-presentation situations, such as presenting oneself in a modest fashion to a stranger or in a self-enhancing fashion to a friend. Participants then completed a variety of seemingly unrelated measures designed to assess self-regulatory abilities, such as persistence on a set of math problems and suppression of emotional responses while watching an upsetting video. Across these experiments, the authors found that self-presentation in unfamiliar or counternormative situations resulted in less self-regulatory ability on a subsequent task. Furthermore, the authors tested whether this relationship held in the other direction. For example, participants first performed the Stroop task, followed by a seemingly unrelated task involving a social interaction. The authors found that taxing self-regulatory resources in this manner led to inappropriate self-presentation in a subsequent social interaction. In sum, these experiments provide evidence suggesting that impression management can affect executive control in an unconscious fashion.

Impression management: opposite-sex interactions

Several studies have elaborated on the work of Vohs et al. (2005) to show how impression management depending on the identity of interaction partners affects executive control in subsequent tasks. For example, for heterosexual individuals, interacting with a member of the opposite sex can often involve high levels of impression management concerns (Baumeister, 1982; Bruch et al., 1989). Karremans et al. (2009) recently investigated the impact of impression management associated with opposite-sex interactions on performance on executive control tasks assessing updating (n-back task) as well as task-switching and inhibition (modified Simon task). In two experiments, the authors found that heterosexual male participants who engaged in a brief interaction with an opposite-sex confederate demonstrated poorer performance on subsequent executive control tasks compared with male participants who interacted with a same-sex confederate. It is important to note that similar to the experiments conducted by Vohs et al. (2005), Karremans et al. (2009) led participants to believe that the social interaction and executive control task components of the experiment were unrelated, suggesting that the influence of the social interaction on executive control operated on an unconscious level.

Interestingly, recent work shows that even the presence of another individual within a specific socio-evaluative context can affect executive control. Dreisbach and Bottcher (2011) had female participants perform a flanker task (Eriksen and Eriksen, 1974), in which participants were asked to indicate the direction of a central left or right pointing arrow that was flanked by arrows pointing in either the same (compatible trials) or different (incompatible trials) direction. Each trial was preceded by a picture of either a landscape or an attractive woman. Concurrently, a fellow student or the romantic partner of the participant evaluated the attractiveness of either the landscapes or the pictures of women. The fellow student or romantic partner performed the evaluation task in the same room as the participant, and was given verbal instructions for the evaluation task such that the participant could hear the instructions. The authors found that participants demonstrated impaired performance on incompatible flanker trials (those trials that invoke executive control) only following pictures of attractive women, but not landscapes. Furthermore, this impairment was only observed in situations where a fellow student or the participant's romantic partner concurrently rated the attractiveness of the pictures of women, but not landscapes. The authors interpret the selectivity of these results as stemming from participants' affective reaction to concurrent evaluation of socially threatening stimuli. Thus, this study suggests the importance of the social context within which we exert executive control. As the authors note, humans typically tend to operate within a social context. Consequently, our social environments are likely to have a pervasive influence on our abilities to exert executive control, even in tasks that are seemingly unrelated to the current social context.

Impression management: interracial interactions

In addition to the sex of our interaction partners, the work of Richeson and colleagues demonstrates that the race of one's interaction partner can also trigger executive control. Richeson and Shelton (2003) found that participants with higher levels of implicit racial bias, assessed via the Implicit Association Test (IAT; Greenwald et al., 1998), demonstrated poorer executive control (i.e., greater Stroop interference) following an interracial interaction than after an interaction with someone of the same race. These results suggest that interracial interactions can have an impact on executive control in seemingly unrelated situations where race is no longer a part of the social context.

In a subsequent study, Richeson et al. (2003) investigated the neural mechanisms underlying the relationship between racial bias, interracial interactions, and executive control. Participants first took part in a behavioral testing session, in which they completed the IAT as well as the Stroop task, following either a same-race or inter-racial interaction with a confederate. At least two weeks later, participants were contacted by a different experimenter and asked to take place in an ostensibly unrelated fMRI study, in which they viewed unfamiliar black and white faces in the context of a spatial perception task. The authors found that neural activity in lateral PFC and the anterior cingulate cortex (ACC) in response to viewing pictures of unfamiliar black, but not white, faces predicted participants' Stroop interference effects following an interracial, but not a same-race, interaction. Importantly, the authors demonstrated that lateral PFC activity was a significant mediator of the relationship between racial bias scores and Stroop interference, suggesting that interracial interactions may temporarily tax executive control abilities supported by PFC, thus leading to impaired Stroop performance.

Although the results of the studies discussed above suggest that interracial interactions can impact executive control, the nature of this influence remains unclear. That is, why might interracial interactions lead to impaired executive control? In follow-up work, Richeson and Trawalter (2005) showed that this relationship appears to stem from the depletion of self-regulation. In one experiment, the authors increased the self-regulatory demand of interracial interactions, by providing participants with false negative feedback about the extent of prejudice revealed by their IAT scores, prior to having the participants engage in the interaction. This led to greater subsequent Stroop interference compared to a control condition in which participants were provided with false negative feedback about their IAT scores that was unrelated to prejudice. In a separate experiment, the authors found that reducing self-regulatory demand, accomplished by providing participants with a script for a discussion about a racially sensitive topic with a black confederate, resulted in less subsequent Stroop interference compared to a control condition in which participants were not provided with a script. Importantly, the manipulation of self-regulatory demands had an impact on Stroop performance only after interracial, but not same-race, interactions. This work suggests potential mechanisms through which interracial interactions may trigger and deplete executive control, namely via anxiety or concern regarding the appearance of being prejudiced (see also Vorauer et al., 2000; Blascovich et al., 2001). Although the majority of the work of Richeson and colleagues has focused on racial bias in white participants, it is important to note that they have also found a depleting impact of implicit racial bias on executive control in black participants following interracial interactions (Richeson et al., 2005). In sum, the work of Richeson and colleagues suggests that interracial interactions can serve as an unconscious trigger of executive control mechanisms, leading to a temporary depletion of these resources.

Interestingly, interracial interactions can also trigger executive control through violation of social mimicry norms (Dalton et al., 2009). As same-race interactions are typically associated with a greater extent of behavioral mimicry compared to interracial interactions, those situations that feature a violation of these mimicry norms can trigger executive control. For example, Dalton et al. (2009) found that same-race interactions featuring a lack of behavioral mimicry and inter-racial interactions featuring higher levels of behavioral mimicry than normal were associated with greater subsequent Stroop interference. These results suggest that counter-normative behavioral mimicry triggered executive control depending on the correspondence between the level of behavioral mimicry and the race of one's interaction partner.

The results discussed thus far may lead one to think that interracial interactions inevitably lead to negative consequences for executive control. Thus, these findings may serve as cause for concern. However, it is important to note that not all interracial interactions necessarily lead to depletion of executive control. In particular, the context in which these interactions occur has the potential to influence their impact on executive control (Babbitt and Sommers, 2011; see also Trawalter et al., 2009). Babbitt and Sommers (2011) manipulated the interaction context for interracial and same-race (all white) dyads to either have a social focus or a task focus. Following the interaction, participants completed the Stroop task as a measure of executive control. The results of this study indicate that the task-focus condition led to a significant decrease in the extent of executive control depletion (i.e., smaller Stroop interference effects) compared to the social-focus condition for black participants in interracial dyads. Although a similar pattern was observed for whites, this effect did not reach significance. In follow-up experiments, Babbitt and Sommers (2011) found that manipulation of interaction context led to changes in self-reported concerns. In particular, white participants reported less concern about coming across as prejudiced, and black participants reported less concern about experiencing prejudice in the task-focus versus social-focus conditions. This study provides evidence suggesting that the framing or context of interracial interactions can have important downstream consequences for executive control. In particular, these results suggest an effective means of reducing the tendency of interracial interactions to deplete executive control.

SOCIAL INTERACTIONS: POSITIVE IMPACT ON EXECUTIVE CONTROL?

Babbitt and Sommers (2011) suggest one possible method of reducing the depleting effects of interracial interactions on executive control. But do social interactions always result in the depletion of executive control resources? Using the metaphor of self-regulatory or executive control resources as a muscle (Muraven and Baumeister, 2000), are there situations in which exercising this muscle can lead to facilitation, rather than fatigue, in subsequent situations reliant on executive control? If so, what types of situations lead to boosts in executive control?

Given the reliance of perspective-taking abilities on executive control (see Decety and Jackson, 2004 for a review), recent work has investigated the hypothesis that social situations that encourage perspective-taking lead to boosts in executive control. Ybarra et al. (2011) primed participants with either cooperative or competitive social goals via description of a future social interaction in either cooperative or competitive terms. This future interaction, in fact, never took place and was used only to prime participants' tendency to engage in perspective-taking. Participants then engaged in a 10 min social interaction with a confederate, after which they completed a seemingly unrelated measure of executive control (Trail Making Test). Ybarra et al. (2011) showed that participants primed with a cooperative social goal demonstrated greater executive control performance compared to those participants in the competitive condition and a no-intervention control condition. Across two follow-up experiments, Ybarra et al. (2011) showed that competitive interactions can also lead to facilitated executive control, provided that participants are encouraged to engage in perspective-taking during these interactions. Based on these results, the authors suggest that situations that encourage perspective-taking can lead to boosts in executive control, perhaps by "warming up" this shared neural resource. However, the authors suggest that challenging social interactions (e.g., interracial interactions for those with higher racial bias) or those that result in withdrawal and a focus on the self rather than on the perspective of another, can lead to depletion of executive control resources.

CONCLUSIONS AND FUTURE DIRECTIONS

As noted in the Introduction, much of the cognitive literature on unconscious information processing in executive control has focused on evidence from visual masked priming paradigms. In this review, we have discussed evidence from several social psychology studies demonstrating that in addition to *stimuli* outside of awareness, unconscious information processing can also refer to *mental processes* that operate without awareness (see Bargh and Morsella, 2008). In particular, we have considered converging evidence from the social domain and highlighted both the pervasive and unconscious influences of social factors on behavioral and neural correlates of executive control. These social factors represent common elements of our everyday lives, including social power roles as well as interactions involving social coordination, behavioral mimicry, and interactions with individuals of the opposite sex and other races.

In addition to recognizing that social factors can unintentionally influence executive control, it is important to consider how this may occur. The studies we have discussed in this review suggest some mechanisms. Social information can unintentionally trigger the establishment of task-sets (e.g., Goldfarb et al., 2011) and pursuit of goals, including those involving self-control (e.g., Ackerman et al., 2009). These task-sets and goals, established via social means such as reading about another individual or trying to adopt someone's perspective, can then guide behavior in a goal-consistent fashion. Information pertaining to social hierarchies and social power roles can also unconsciously influence executive control abilities, such as active maintenance of task- or goal-relevant information (e.g., Guinote, 2007; Smith et al., 2008) and related PFC activity (e.g., Boksem et al., 2009). As noted by Miller and Cohen (2001), the establishment and maintenance of goals and subsequent biasing of behavior in line with these goals serves as the principal function of PFC.

Another way in which social information can affect executive control involves the depletion of self-regulatory resources. As suggested by Vohs et al. (2005); Finkel et al. (2006); and Dalton et al. (2009) social interactions proceeding in an inefficient or counter-normative fashion may deplete self-regulatory resources. As a result, this depletion can have an impact on subsequent tasks dependent on these same self-regulatory resources, such as executive control tasks. Work by Richeson and colleagues (e.g., Richeson et al., 2005) has also shown that interracial interactions may deplete self-regulatory resources, perhaps due to concerns about appearing prejudiced, and lead to subsequent executive control impairments. Furthermore, activity in PFC appears to mediate this relationship (Richeson et al., 2003).

The studies discussed in this review have demonstrated several ways in which social factors can influence executive control in an unconscious fashion. However, they also suggest additional questions and avenues for further research. We offer two such avenues here. First, which factors determine whether a social interaction impairs or boosts executive control? Preliminary evidence suggests that interactions involving perspective-taking can lead to facilitation of executive control (Ybarra et al., 2011). This finding suggests the potential for using perspective-taking manipulations to offset the self-regulatory depletion caused by effortful interactions, such as during a high-maintenance interaction, or when interacting with someone of a different race. Further research is necessary to determine other social factors that can boost executive control. Dalton et al. (2009) have suggested that behavioral mimicry in the context of close relationships may serve to replenish executive control resources. The extent to which perspective-taking and behavioral mimicry can boost or replenish executive control should be tested across a variety of different social contexts, as this could have important consequences for the successful utilization of executive control and self-regulation in our daily lives. Additionally, further research is needed on the neural correlates of how social interactions affect executive control. Previous neuroimaging studies have largely been unable to investigate the effects of naturalistic social interactions on neural activity due to the constraints of functional neuroimaging methods. However, recent work has introduced novel methods for implementing online, face-to-face social interactions during fMRI scanning (Redcay et al., 2010), and these methods holds great promise for future work investigating the impact of social interactions on executive control.

Second, what is the duration of the impact of social priming and social interactions on executive control? In the case of the social priming technique, Goldfarb et al. (2011) found an impact on Stroop performance only in the block immediately following the dyslexia priming manipulation. This suggests that social priming effects are of short duration and may not have as far-reaching consequences as a taxing social interaction. In further support of this idea, evidence from the power priming literature suggests that priming of power constructs yields similar, but less impactful, behavioral consequences compared with the actual possession of power (see Smith and Galinsky, 2010 for a review). The majority of studies employing social interactions have tended to investigate their impact on executive control for tasks immediately following the social interaction. Thus, the duration of these effects requires further study in order to determine the extent of their influence.

Additionally, it is important to note that although social information can unconsciously trigger executive control, this does not mean that all of our behavior is beyond our conscious control (see Suhler and Churchland, 2009). Rather, it is likely that both consciously and unconsciously processed information can trigger executive control depending on the situation, and that both consciously and unconsciously triggered control work in concert to efficiently guide behavior. Further research is clearly necessary to elucidate the similarities and differences between conscious and unconscious control mechanisms. In addition, further specification of the types of factors that can influence executive control will allow for identification of ways to combat these influences, particularly when they lead to undesirable behavioral consequences (e.g., depletion of self-regulatory resources).

Consideration of the unconscious influence of social factors on executive control holds a great deal of promise for future research. Indeed, based on the findings discussed in this review, it is critical to ask not only *whether* social information can unconsciously influence executive control, but also *how* these effects occur. In his seminal article on the social function of intellect, Humphrey (1976) described studying the recovery of vision in a rhesus monkey that had been kept in a cage in the laboratory. Although the monkey's recovery was somewhat limited within the laboratory, she showed a great improvement in spatial vision when she was allowed to spend time outdoors. Humphrey thus notes that "The limits on her recovery had been imposed directly by the limited environment in which she had been living" (1976, p. 308). In a similar fashion, a great deal of experimental psychological research involves testing participants' executive control abilities in isolation within the "cage" of the laboratory. However, in our daily lives, we are nearly always engaged in a social context. In order to better understand executive control processes, we must move beyond only studying participants in the limited social environment of the laboratory, and also consider the influence of social factors present in our everyday lives. Thus, greater consideration of the interplay between social factors and executive control may allow us to gain a deeper understanding of the mechanisms underlying regulation of human behavior.

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