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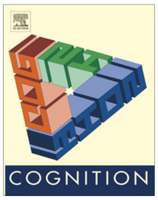

Subliminal priming of intentional inhibition

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ABSTRACT

Intentional choice is an important process underlying human behaviour. Intentional inhibition refers to the capacity to endogenously cancel an about-to-be-executed action at the last moment. Previous research suggested that such intentional inhibitory control requires conscious effort and awareness.

Here we show that intentional decisions to inhibit are nevertheless influenced by unconscious processing. In a novel version of the Go/No-Go task, participants made speeded keypress actions to a Go target, or withheld responses to a No-Go target, or made free, spontaneous choices whether to execute or inhibit a keypress when presented with a free-choice target. Prior to each target, subliminal masked prime arrows were presented. Primes could be congruent with the Go or No-Go arrows, or neutral. Response times and proportion of action choices were measured. Primes were presented at latencies that would give either positive or negative compatibility effects (PCE, Experiment 1, and NCE, Experiment 2, respectively), based on previous literature.

Go-primes at positive-compatibility latencies facilitated speeded response times as expected, but did not influence number of choices to act on free-choice trials. However, when Go primes were presented at negative-compatibility latencies, "free" decisions to inhibit were significantly increased. Decisions to act or not can be unconsciously manipulated, at least by inhibitory mechanisms. The cognitive mechanisms for intentionally withholding an action can be influenced by unconscious processing. We discuss possible moral and legal implications of these findings.

1. Introduction

The idea of voluntary control over what to do, and indeed whether to do it at all- is a fundamental but controversial feature of human nature. For example, legal judgements about criminal behaviour are based on the view that the agent could have refrained from the criminal act. Further, the feeling of choosing to act in certain ways while resisting others is a common experience in everyday life. We use the term 'intentional inhibition' to refer to the process of voluntarily withholding the execution of an action at the last moment. Inhibition of impending action triggered by external stimuli has been widely studied, notably in stop-signal tasks (Logan, Cowan, & Davis, 1984; Verbruggen & Logan, 2008). In such cases, inhibition can be clearly distinguished from an early decision not to prepare an action. We use the term inhibition to mean an intervention mechanism that "applies the brakes" and actively overrides impending movement (see Aron (2011) for a review of these mechanisms).

Inhibition in this sense can result either from an external 'stop' signal, or from an internal decision. Internally-generated inhibition has been much less studied, although its importance in theories of cognitive control is recognised (Aron, 2011; Filevich, Kühn, & Haggard, 2012). Intentional

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inhibition has traditionally been linked with a conscious form of voluntary self-control. Libet, Gleason, Wright, and Pearl (1983) classically argued that the short delay between awareness of intention and movement onset was sufficient to allow a 'conscious veto' over action. On this view, people may not have free will, but they may have 'free won't'. Recent work in social psychology continues to emphasise the importance of conscious effort in refraining from apparently rewarding actions (Baumeister, Masicampo, & Vohs, 2011). In both instances, intentional inhibition seems like a paradigm case for a conscious form of "agent causation" (Kane, 1996a, 1996b). Importantly, however, it is quite possible that a capacity for internally-generated inhibition exists, yet its triggering could be unconscious.

Here we ask whether intentional inhibition can be influenced by external stimuli that are not consciously perceived. It is widely accepted that endogenous 'free' actions may nevertheless be influenced by external stimuli, including subliminal stimuli that are not consciously perceived, but whose informational content is processed in the nervous system. For example, subliminal perceptual priming can manipulate the subjective experience of the agency of a "free" action (Aarts, Custers, & Wegner, 2005; Linser & Goschke, 2007; Sato, 2009; Sebanz & Lackner, 2007; Wenke, Fleming, & Haggard, 2010). Moreover, subliminal priming can also influence a "free" decision regarding which of a number of alternative actions one selects.

However, some psychologists have argued that inhibition has a special relation to conscious awareness. Specifically, inhibition of action may be a necessarily conscious and effortful cognitive control process, and thus immune to unconscious information-processing (e.g., Dehaene et al., 2003). We cannot resist a prepotent action without consciously intending to resist it, and knowing that we are doing so. This view receives some support from anecdotal accounts of intense subjective experience of trying to overcome urges to prepotent action (St. Augustine, 2006). Overall this would suggest that intentional inhibition should not be manipulable by subliminal exogenous stimuli. Even if we do not really have 'free will', 'free won't', in the sense of top-down inhibitory self-control, might remain a distinct cognitive process, relatively free from such unconscious environmental determinants.

Subliminal stimuli can indeed influence inhibitory processing in externally-instructed forced-choice tasks. In many such studies, primes and targets are directional arrows indicating whether to make a left or right keypress. Targets preceded by congruent primes show decreased response times, and targets preceded by incongruent primes show increased response times, both relative to neutral primes (Neumann & Klotz, 1994). This positive compatibility effect (PCE) is thought to reflect facilitation of the primed response and/or inhibition of the alternative response. In contrast, in the negative compatibility effect (NCE; Eimer, 1999; Eimer & Schlaghecken, 1998) the congruent prime paradoxically inhibits responding. By increasing the stimulus onset asynchrony (SOA) between the onset of prime and target, the normal facilitatory effect of the congruent prime is reversed. Now a prime congruent with the target slows responses whilst the incongruent prime speeds responses.

One prominent theory for the process driving the PCE and NCE effects hypothesises that subliminal primes exert their influence by motor preparation and then inhibition of relevant responses. Initially, a prime will exert a facilitatory influence upon the appropriate motor response, activating it to a sub-response-threshold level. If a congruent supraliminal target appears, the facilitatory activity caused by the prime coincides and combines with that of the target, resulting in a faster response. However, the sub-threshold activation caused by the prime is assumed to be transient. If no further congruent evidence arrives shortly after the prime, the prime-induced activation is followed by a process of auto-inhibition, suppressing the activity below baseline. This process is thought to protect perceptual systems from oversensitivity to noise (Blankenburg et al., 2003). Long prime-target SOAs mean that the target appears during the auto-inhibitory period, thus resulting in the slowed responses that characterise the NCE. The NCE has also been explained in other ways. In particular, the interaction between the prime and the subsequent mask has been argued to facilitate perception of the alternative target that is not primed, thus producing a negative compatibility effect (Lleras & Enns, 2004; Verleger, Jaśkowski, Aydemir, van der Lubbe, & Groen, 2004). This question, which remains controversial, is revisited in the discussion.

Most previous subliminal priming studies focussed on decisions about what action to make, in two-alternative forced choice paradigms (Schlaghecken & Eimer, 2004). However, recent research has extended the method to decisions whether to act at all, by studying priming of inhibition in unimanual Go/No-Go tasks Hughes and colleagues used masked subliminal primes to influence responses in a Go/No-Go paradigm (Hughes, Velmans, & De Fockert, 2009). Participants were instructed to prepare a speeded response with a designated hand. They should respond rapidly following a Go stimulus, but inhibit execution of this action following a No-Go signal. Left and right arrow targets were preceded by left, right and neutral (double arrow) masked primes, at latencies appropriate for PCE. One arrow direction was designated as the Go and the other as the No-Go target. They found that Go targets preceded by a Go prime indeed elicited faster responses than Go targets preceded by a neutral prime, while a No-Go prime slowed responses to a Go target, again compared to neutral. Event-related potentials to No-Go targets revealed that fronto-central N2 and P3 components, previously associated with response inhibition (Falkenstein, Hoormann, & Hohnsbein, 1999), were modulated by the subliminal primes: No-Go primes reduced the magnitude of the negative N2 component (~300 ms after the target) elicited by No-Go targets, compared to effects of neutral and Go primes. This suggests that unconscious No-Go primes contributed to action inhibition. Thus, Hughes et al. (2009) argue that unconscious exogenous cues can indeed influence inhibitory control processes.

In another Go/No-Go experiment (van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008), a Go signal (black ring) indicated that an action should be performed, unless it was preceded by the No-Go signal (grey circle). If the stimulus onset asynchrony (SOA) between No-Go and Go signals was sufficient, the No-Go signal was consciously perceived. However, it could be rendered unconscious by reducing the SOA such that the Go signal masked its presence. These unconscious No-Go signals reduced the number of GO responses, and also slowed response times on those trials where a response did occur. In an fMRI experiment, the same unconscious No-Go signals elicited activity in frontal inhibitory areas, especially the IFC and pre-SMA (van Gaal, Ridderinkhof, Scholte, & Lamme, 2010). Finally, unconsciously presented Stop signals presented prior to a Go signal in the classic stop signal task (Logan, Cowan & Davids, 1984), reduced the number of executed responses, or slowed RTs on trials where responses did occur (van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009).

These results suggest that inhibition elicited by an external signal can be unconsciously modulated by subliminal primes, just like action selection decisions between alternative responses. However, inhibiting one response is not the same choosing another (Aron, 2011; Simmonds, Pekar, & Mostofsky, 2008). Accordingly, inhibitory priming and action-selection priming appear to work in different ways. First, inhibitory priming recruits a specific set of frontal brain areas associated with stopping prepotent actions, distinct from the areas that accumulate evidence about alternatives (Van Gaal et al., 2010). Second, inhibitory priming has effects even when the decision to inhibit comes after an initial decision to act – as in the stop-signal task. This late inhibition of action implies a late braking or cancellation process. In contrast, priming of action selection is considered to bias early accumulation of evidence in favour of one response.

It remains unclear whether intentional decisions to inhibit action can be unconsciously influenced in the same way. Indeed, no previous study has shown that free, internally-generated choices whether to execute or inhibit action can be unconsciously primed. The traditional association between inhibition and conscious, effortful control (Dehaene et al., 2003; Mayr, 2004; Vohs & Baumeister, 2013) might suggest that they cannot be. In the present study we directly tested this claim by investigating whether unconscious primes can, in fact, influence intentional inhibition in a situation where participants have the free choice to either execute a simple action, or to decide at the last possible moment to refrain from executing it.

We used a modified Go/No-Go task in which participants were asked to prepare a single action (a keypress) and await the presentation of one of three target stimuli: One target indicated the participant must perform the action (forced Go), one indicated the inhibition of the action (forced No-Go), and the third target indicated participants had the free choice to either act or inhibit (free Go or No-Go). Targets were preceded by masked subliminal primes that were congruent with the Go or No-Go targets, or were neutral.

Three experiments were run, using prime-target SOA values which were known to produce PCE and/or NCE priming effects. Thus we aimed to measure whether subliminal Go or No-Go primes modulate the execution or inhibition of responses that the participant freely chooses whether to make or not. Experiments 1 and 2 used left and right pointing targets and primes, Experiment 1 with PCE and Experiment 2 with NCE timings. Experiment 3 combined both types of priming and used upward and downward pointing arrows. Clear predictions could be made regarding the outcome of these results: Go primes at PCE latency would facilitate and thus speed up forced Go responses, whereas NoGo primes would inhibit, thus slow down, forced Go responses relative to Neutral primes. The opposite RT pattern was predicted for priming at NCE latencies (as per Eimer (1999)). We predicted that free-choice RTs should be influenced by primes in the same way was forced choices. If priming indeed alters levels of excitation/inhibition in brain motor circuits, it should also affect the outcome of ‘free’ choices. Go primes at PCE latency should increase the probability of choosing to act, and NoGo primes should increase the probability of choosing to inhibit. Primes at NCE latency should have the opposite effect. These predictions were used to guide analysis of the data.

2. Method

2.1. Design

Three experiments were designed to measure the effects of subliminal priming on volitional action and inhibition in a Go/No-Go paradigm. Stimulus timing was designed to elicit PCE (Experiment 1), NCE priming (Experiment 2), or both within the same experiment (Experiment 3). The designs were otherwise largely similar.

The basic paradigm involved participants making Go, No-Go or Free Choice responses to visual target stimuli using one hand only to make keypress responses. A trial consisted of a central fixation cross, followed by a visual subliminal priming sequence (see later) culminating in a supraliminal target stimulus. In Experiments 1 and 2, Target stimuli were either left, right, or double-headed (left and right) arrows. In Experiment 3, target stimuli were either up arrows, down arrows, or double-headed arrows. In all experiments, there were 25% Go targets, 25% NoGo targets and 50% Free Choice targets. Each target could be preceded by Go, NoGo or Neutral primes, with equal probability.

In all experiments, participants were instructed that each trial would start with a fixation cross, and would be followed by some “random flashing shapes”. Participants were instructed to prepare a keypress action, on every trial, beginning their preparation from the onset of fixation. Each trial would culminate in a clearly visible arrow stimulus, that could point either left or right (Experiments 1 and 2), up or down (Experiment 3), or in both directions (all experiments). They were instructed that one of the uni-directional arrows was a Go signal, upon which they must make the prepared action as rapidly as possible. Speed of response times was stressed, again emphasising the need for action preparation from the beginning of every trial. This was further stressed as there was a one second response window from the onset of any target stimulus within which to make a response. The opposite uni-directional arrow was designated as the No-Go target, upon which participants were instructed to withhold the keypress action and wait until the next trial.

Double-headed arrows indicated a Free Choice trial. Participants were instructed to make an in-the-moment decision regarding whether to press the key, or inhibit the keypress action on such trials. They were informed that it made no difference to the experimental outcome if they chose to act or not: the decision on each trial was arbitrary. They were encouraged to decide at the last moment, avoiding strategies like alternation of action and inhibition decisions. They were also asked to ensure that they sampled from both action and inhibition options throughout the experiment. This was not an explicit instruction to "equalise" act and inhibition choices, but just encouragement to not bias extremely to one choice or the other. The format of this instruction relates to a fundamental feature of experiments on volition. There is an inherent tension between allowing participants a truly free choice, and the experimental requirement to have adequate data relating to both possible responses. Exclusion criteria were defined to remove participants with outlying distribution of free choices, thus ensuring a sufficient number of each possible response for reliable estimation. Participants with a proportion of free-choice actions ±2.5 SD from sample mean were excluded (see Section 2.2 for details).

There were important difference between experiments as to which uni-directional arrows were Go and No-Go targets, and which response hand to use. In Experiments 1 and 2, at the beginning of each of four experimental blocks, participants were informed which uni-directional arrow – left or right – was the Go target for the entirety of that block. Participants were instructed to use the hand congruent with the Go target to respond throughout the block. Handedness was counterbalanced across participants and blocks in an ABBA fashion. That is, Go targets and primes were arrows that were spatially compatible with the hand used as the Go response. NoGo primes and targets might, in principle, produce spatial incompatibility effects (Simon, 1969). To control for this possibility, Experiment 3 used up or down arrows at Go/NoGo targets, and right hand responses. In all three experiments, only right-handed participants were tested.

The experiments used different forms of action-priming, produced by altering the stimulus-onset-asynchrony (SOA) between prime and target stimuli (or between mask and target see Fig. 1). Short SOAs of 52 ms were used to produce PCE priming (Experiment 1), whereas longer SOAs of 172 ms were used for NCE priming (Experiment 2; Lingnau & Vorberg, 2005; see Section 2.4 for further details). Experiment 3 used both PCE and NCE priming in separate blocks of a within-subject design. Blocking of PCE and NCE was preferred to randomisation, because trial-by-trial changes in prime-target SOAs reportedly increase task difficulty (Lingnau & Vorberg, 2005).

The frequency of action and inhibition, and the latency of all responses made were measured in Go, No-Go and Free Choice trials. Unbeknownst to the participants, each target stimulus was preceded by a backwards meta-contrast masked prime arrow, which could point either left, right, or be a superimposition of left and right arrows (up/down arrows in Experiment 3; see Fig. 1; stimulus design as used by (Lingnau & Vorberg, 2005). Thus primes could be either Go, No-Go or Neutral primes based upon their stimulus congruency. Therefore, Experiments 1 and 2 investigated the effects of prime-response congruency on target response, whilst Experiment 3 employed a 2 (latency effect: NCE vs PCE) × 3 (prime) design.

2.2. Participants

All participants were recruited from the UCL participant pool. All were self-reported right-handers, had normal or corrected-to-normal vision and were paid £7.50 for the hour-long total duration of the experiment. Twenty-two participants (9 female) took part in Experiment 1, mean age 26.3 (SD 5.29). Twenty-three participants took part in Experiment 2, but one was excluded based on prior criteria, because of an excessive tendency to prefer action in free-choice trials (91.1%, >2.5 standard deviations from sample mean), which rendered their data on inhibition choices insufficient and potentially unreliable. This left a sample of 22 (12 female, mean age 26.9, SD 8.76). Twenty-three participants took part in Experiment 3. Again, one was rejected for making so few freely-chosen actions in Choice trials (1.3%, <2.5 standard deviations from sample mean) that their data could not be meaningfully analysed, leaving a sample of 22 (14 female, mean age 22.4, SD 3.46).

2.3. Procedure

All experiments used an identical procedure in terms of participant briefing and experimental structure. Experiments 1 and 2 consisted of 384 trials, split over four blocks, each block varying the response hand and Go-Arrow direction, as described in Section 2.1. Experiment 3 consisted of 768 trials over 8 blocks, each block consisting exclusively of PCE or NCE trials, with alternating blocks. For both the forced Go and No-Go target conditions, 32 trials were presented for each of the three primes (and for each of the PCE/NCE Latencies in Experiment 3). For the free Choice trials, 64 trials were presented for each of the three primes. Thus, if subjects chose to act or withhold action on similar numbers of trials, the dataset would sample across free and forced action and inhibition in a balanced way.

Between each block, participants were allowed a short self-terminated break. Prior to the main experiment, participants undertook a practice session consisting of two blocks, one for each hand (in Experiment 3, two blocks, one for each of the PCE and NCE conditions). Practice trials only used the neutral prime, and involved 6 trials each of the Free Choice and Forced conditions, thus each practice block contained 18 trials.

After the main experimental session was complete, participants were informed of the presence of the subliminal primes, and were then asked to take part in a short final session to collect data on the discriminability of the primes. One block of trials presented participants with stimulus sequences similar to those in the main experiments, except that only free choice targets were presented. Participants were instructed to ignore the targets. Instead they were asked to concentrate carefully in the period where the prime appeared – often detectable as a "small white flash" – and try and decide whether the prime was a left, right, or neutral prime, and make unspeeded but forced choices. They were instructed to guess

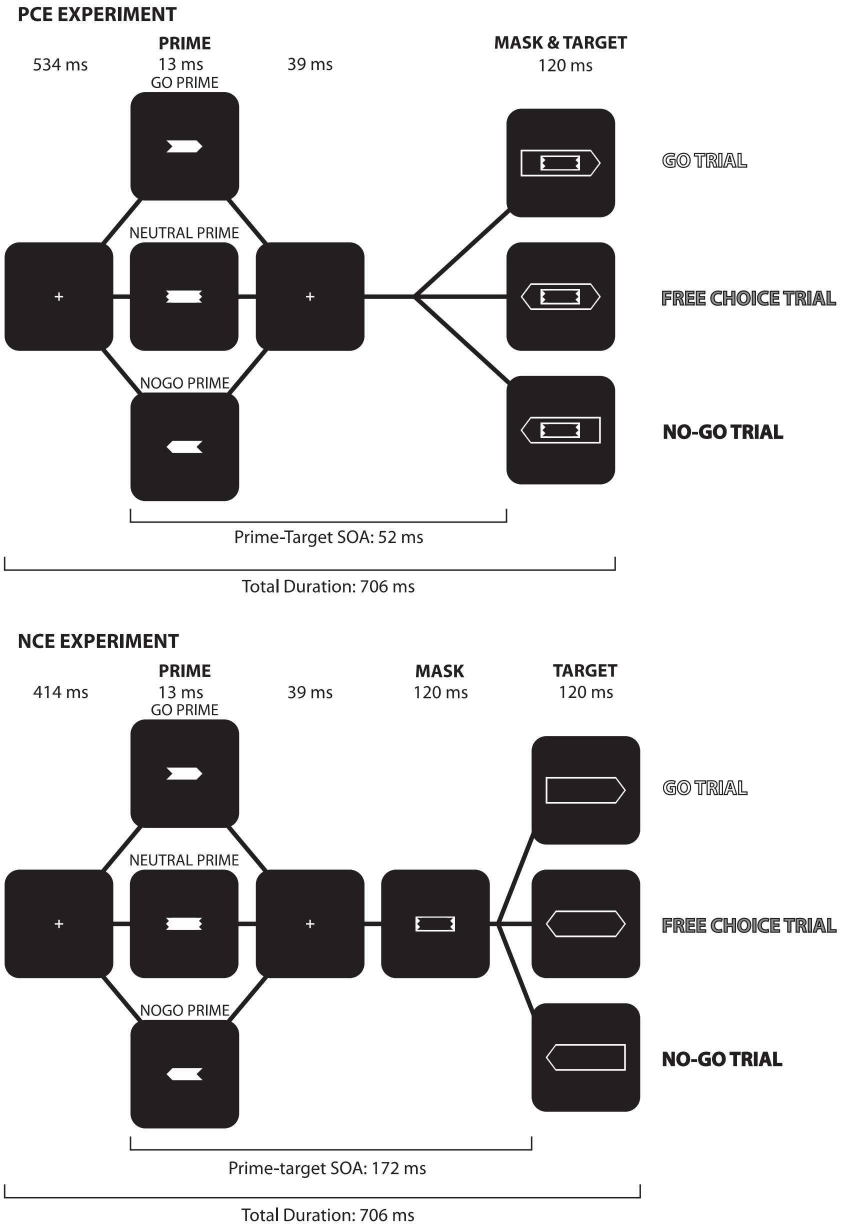

Fig. 1. Stimulus schema showing the prime–mask–target timings used to produce PCE and NCE priming effects. Experiment 1 used the PCE stimuli shown in the top panel. Experiment 2 used the NCE stimuli shown in the bottom panel. Experiment 3 used both PCE and NCE timings. Experiment 3 also used up/down arrows produced by rotating all stimuli by 90°.

if uncertain. Thus 10 repetitions of each of the three prime stimuli were presented. The entire experiment lasted around 1 h.

2.4. Stimuli

Stimuli were presented on a PC using the Psychophysics Toolbox version 3 for Matlab (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997), on a CRT monitor with a 75 Hz refresh rate, using a white-on-black colour scheme. Participants were seated at a comfortable viewing distance and used a customised button box to make responses. Stimulus dimensions are shown in Supplementary Fig. 1, and were based on those used by Lingnau and Vorberg (2005). At the start of each trial the central fixation cross, subtending 0.2°, was shown for a period of 534 ms (Experiment 1) or 414 ms (NCE experiment), maintaining an overall trial duration of 1586 ms (including response window; 706 ms from onset of fixation to offset of target) across both experiments, and building on timings established previously (Lingnau & Vorberg, 2005). Each prime stimulus was presented for 13 ms (1 frame at 75 Hz refresh rate), followed by a reintroduction of the fixation cross for 39 ms.

Following this the meta-contrast mask appeared for 120 ms, a stimulus sequence found to make the discrimination of the prime stimulus not possible (Lingnau & Vorberg, 2005). Prime-Target SOA interval is the critical factor in determining the direction of priming: Experiment 1 used PCE priming with a prime-target SOA of 52 ms (Lingnau & Vorberg, 2005), which meant that the target arrow onset at the same time as the mask and thus surrounded the mask (see Fig. 1, top), also lasting for 120 ms. Experiment 2 used NCE priming with a prime-target SOA of 172 ms, which meant the target arrow onset immediately after the offset of the mask, and remained onscreen for a further 120 ms.

3. Results

3.1. Prime discrimination results

Discrimination test results were measured by computing the mean percentage of trials correctly discriminated, and comparing this against the chance-level of 33% correct using single sample *t*-tests. Participants in Experiment 1 (using PCE timings) could not consciously discriminate primes, mean correct 35.2%, SD 9.83. A *t*-test was used to compare this to the chance level of 33.3%: $t(21) = 0.847$, $p = .406$. Nor could they do so in Experiment 2 (NCE timings), M 31.5%, SD 13.2; $t(21) = 0.633$, $p = .534$. In Experiment 3, mean correct discriminability score was 33.9%, SD 6.73, and again not significantly different from chance, $t(21) = 0.412$, $p = .684$. We also computed d′ measures of discrimination for each prime in each experiment, and used repeated uncorrected *t*-tests to compare these to a value of 0 (no discrimination possible). The maximum d′ was 0.21, and no *t*-test was significant, further suggesting that no conscious discrimination of the primes was possible (full values of d′ and *t*-test results are shown in Supplementary Table 1).

3.2. Response times

Correct response times were classified as either "forced Go trials" (responses to Go signals), or-free choice Go trials (when participants chose to press the button in free choice trials). Response times were further classified according to the prime (Go/No-Go/Neutral) preceding the target stimulus, thus producing a 2 × 3 repeated measures ANOVA design (2 × 2 × 3 for Experiment 3, where PCE/NCE Latency was also varied). Median response time in ms was taken for each participant for each condition.

3.2.1. Experiment 1 (PCE)

Fig. 2 shows the summary of response times for Experiment 1. There were significant main effects of trial type, $F(1,21) = 9.45$, $p < .006$, and of prime type, $F(2,42) = 18.0$, $p < .001$, but no significant interaction, $F(2,42) = 1.39$, $p = .261$. Planned contrasts were performed for each trial type, because we had a specific prior interest in whether primes would significantly influence free choice responses. In forced Go trials, response times were faster for Go prime trials compared to Neutral primes, $t(21) = 3.15$, $p = .002$, and slower for No-Go primes compared to Neutral primes, $t(21) = 3.08$, $p = .003$. In free choice Go trials, response times were slower for No-Go primes compared to Neutral primes, $t(21) = 5.75$ $p < .001$, but there was no difference in response times between Go and Neutral prime trials, $t(21) = 0.47$, $p = .322$. On average, over all prime types, free choice Go responses were 37 ms slower than forced Go responses. (Full *F*, *t*, and response time differences are in Supplementary Tables 2 and 3).

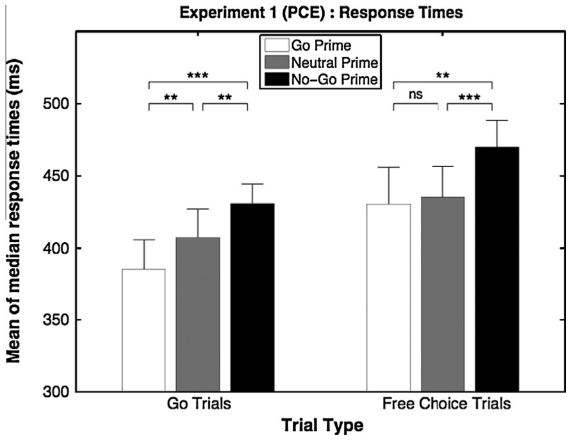

Fig. 2. Sample mean of median response times in Experiment 1 (forced Go and Free Choice actions only). Error bars show standard error of mean. $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$; $^{+}$trend, $p < .1$.

3.2.2. Experiment 2 (NCE)

Fig. 3 shows the summary of response times for Experiment 2. There were significant main effects of trial type, $F(1,21) = 44.6$, $p < .001$, and of prime type, $F(2,42) = 31.1$, $p < .001$, but no interaction, $F(2,42) = 0.772$, $p = .466$. Planned contrasts were performed because of our prior interest in the effects of priming in free choice trials. In forced Go trials, response times were slower for Go prime trials compared to Neutral primes, $t(21) = 5.21$, $p < .001$, and slower for No-Go primes compared to Neutral primes,

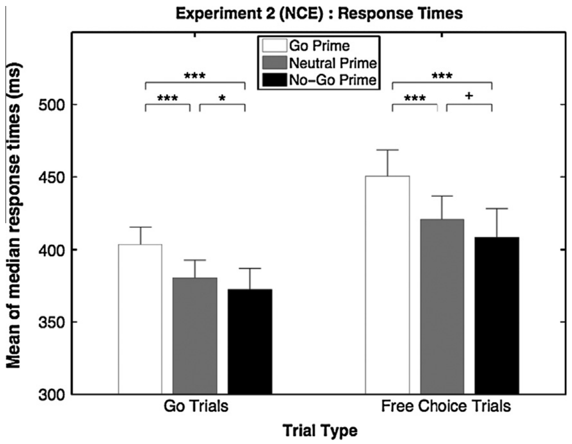

Fig. 3. Sample mean of median response times in Experiment 2 (forced Go and Free Choice actions only). Error bars show standard error of mean. $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$; $^{+}$trend, $p < .1$.

$t(21) = 1.98$, $p = .031$. In free choice Go trials, response times were slower for Go primes compared to Neutral primes, $t(21) = 3.82$, $p = .001$, and there was a trend for No-Go primes to speed responses compared to Neutral primes, $t(21) = 1.56$, $p = .067$. On average, over all prime types, free choice Go responses were 42 ms slower than forced Go responses. (Full F, t, and response time differences are in Supplementary Tables 4 and 5).

3.2.3. Experiment 3

First, response times (excluding No-Go trials) in Experiment 3 were analysed in a 2 (Latency Effect, PCE/NCE) × 2 (Trial Type) × 3 (Prime type) repeated measures ANOVA (see Supplementary Table 2 for full results). There were significant main effects of Latency Effect, $F(1,21) = 7.24$, $p = .014$, and Prime, $F(2,42) = 4.48$, $p = .029$, but no main effect of Trial Type $F(1,21) = 1.62$, $p = .217$. The only significant interaction was between Prime and Latency Effect, $F(2,42) = 21.6$, $p < .001$, supporting the fact that the PCE and NCE paradigms reverse the response time effects of priming magnitude (as seen comparing Experiments 1 and 2). There was no three way interaction with trial type, $F(2,42) = 1.87$, $p = .177$.

As for Experiments 1 and 2, we performed planned contrasts because of our prior interest in priming effects on Free Choice trials. We therefore split trials by choice Type (Forced Go and Free Choice Go) and compared results across Latency Effect (PCE vs NCE). Fig. 4 shows response times for Forced Go trials. There was a main effect of Prime, $F(2,42) = 3.44$, $p = .041$, but none of Latency Effect, $F(1,21) = 1.64$, $p = .241$. There was a significant interaction between the two factors, $F(2,42) = 27.8$, $p < .001$, due to the expected opposite effects of PCE and NCE. Using simple effects testing to investigate this interaction, Go primes at PCE latency produced faster responses compared than Neutral primes, $t(21) = 2.74$, $p = .006$, and No-Go primes produced slower response times, $t(21) = 3.75$, p .001. At NCE latency Go primes produced slower responses than Neutral primes, $t(21) = 5.77$, $p < .001$, but there was no significant difference between No-Go and Neutral primes, $t(21) = 0.52$, $p = .305$. (Supplementary Tables 6 and 7 show full F, t and response time difference values).

Fig. 5 shows response times for Free Choice trials in which actions were made. These data were analysed using the same planned contrasts as forced-choice latencies. There was a main effect of Latency Effect, $F(1,21) = 10.7$, $p = .004$, no main effect of Prime, $F(2,42) = 2.31$, $p = .134$, and a strong interaction between the two, $F(2,42) = 8.90$, $p = .002$. Simple effects showed that Go primes at PCE latency did not produce faster response compared to Neutral prime, $t(21) = 0.277$, $p = .392$, but No-Go primes did slow responses, $t(21) = 6.55$, $p < .001$. Go primes at NCE latency did not significantly slow response times, $t(21) = 0.848$, $p = .203$, nor did No-Go primes facilitate them $t(21) = 1.10$, $p = .143$.

3.3. Forced response behavioural errors

In forced choice trials, errors were few. In Experiment 1, in forced Go trials, mean error-of-omission rate was 4.17% (SD 7.3), whilst in No-Go trials mean error-of-commission rate was 5.2% (SD 4.74). In Experiment 2, in forced Go trials, mean error-of-omission rate was 0.99% (SD 1.07), whilst in No-Go trials mean error-of-commission rate was 2.4% (SD 2.45). In Experiment 3, in the PCE condition, Go trials produced 4.1% (SD 7.8) and No-Go trials 7.2% (SD 7.3) errors. In the NCE conditions, Go trials produced 3.8% (SD 7.6) and No-Go 6.6% (SD 7.7) errors. Errors were not further analysed.

3.4. Free choice behaviour

3.4.1. Experiments 1 & 2

The response rates for Free Choice trials were analysed to investigate how subliminal priming influenced participants' choices to execute or inhibit actions. In The proportion of actions in Free Choice trials was 58.8% (SD 18.3), 56.5% (SD 14.1), and 50.3% (SD 3.46) for Experiments 1, 2 and 3 respectively. Experiments 1 and 2.

Fig. 6 shows the rate at which participants chose to act in free choice trials as a function of the preceding

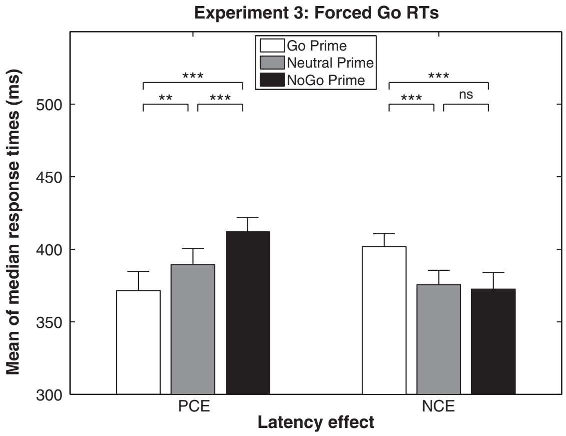

Fig. 4. Sample mean of median response times in Experiment 3 (forced Go trials only). Error bars show standard error of mean. $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$; $^{+}$trend, $p < .1$.

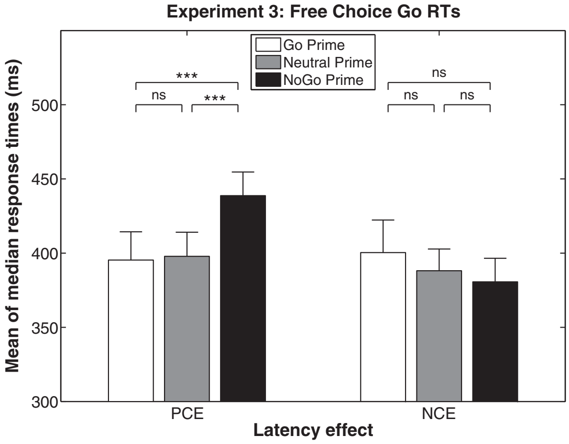

Fig. 5. Sample mean of median response times in Experiment 3 (Free Choice Go trials only). Error bars show standard error of mean. $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$; $^{+}$non-significant trend, $p < .1$.

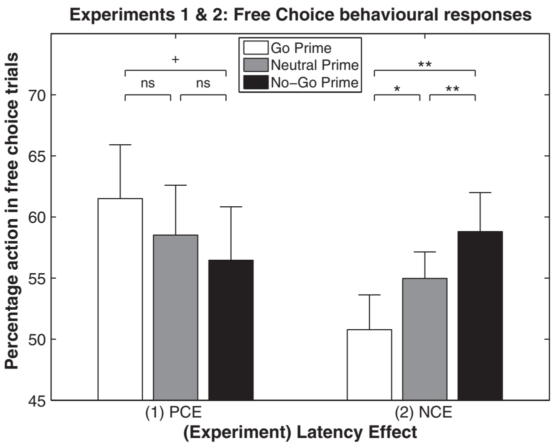

Fig. 6. Experiment 1 and 2: Mean percentage of Free Choice trials in which participants chose to act rather than inhibit responses, as modulated by prime condition. Error bars show standard error of mean. $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$; $^{+}$trend, $p < .1$.

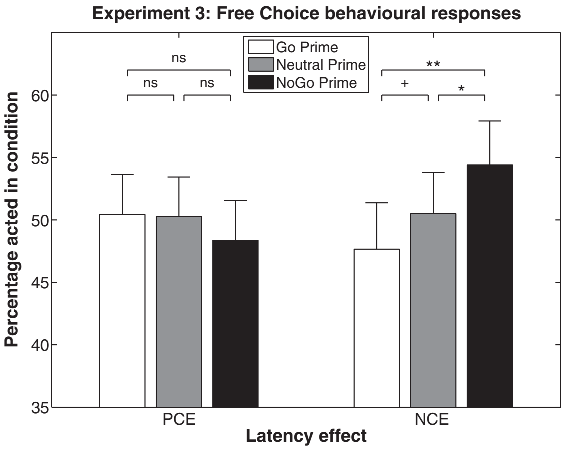

Fig. 7. Experiment 3: Mean percentage of Free Choice trials in which participants chose to act rather than inhibit responses, as modulated by prime condition. Error bars show standard error of mean. $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$; $^{+}$trend, $p < .1$.

subliminal prime, in both the PCE and NCE experiments. A 3×2 mixed ANOVA using Latency effect (PCE/NCE) and Prime type showed no significant main effect of Latency $F(1,42) = 0.719$, $p = .401$, or Prime type was found, $F(2,84) = 0.372$, $p = .690$, but a highly significant interaction between the two factors $F(2,84) = 7.08$, $p = .001$.

Simple effects within each experiment was used to explore this interaction. In Experiment 1 (PCE priming), there was no significant main effect of priming on behavioural choice, $F(1.55,32.6) = 1.7$, $p = .198$, Greenhouse–Geisser corrected for sphericity. However, in Experiment 2 (NCE priming) prime type significantly influenced behavioural choice, $F(1.53,32.1) = 6.93$, $p = .006$, Greenhouse–Geisser corrected for sphericity. Follow-up testing showed that Go primes produced a significant 4% reduction in the proportion of free-choice actions relative to Neutral, $t(21) = 1.87$, $p = .038$. Conversely, a No-Go prime increased response rate by 3.8%, $t(21) = 2.56$, $p = .009$. Note that these differences are in the predicted direction for inhibitory effects of NCE priming. Overall, this pattern of results suggests that the volitional free choice to act or inhibit can be non-consciously influenced by NCE priming, but the effect of PCE priming is less clear (full F, t and response difference values in Supplementary Tables 9 and 10).

3.4.2. Experiment 3

Response rates to Free Choice trials in Experiment 3 are shown in Fig. 7 and were analysed using a 3×2 repeated measures ANOVA using Latency Effect and Prime as factors. There were no main effects of Latency Effect, $P(1,21) = 0.423$, $p = .518$, or Prime, $F(2,42) = 1.88$, $p = .166$, but a significant interaction between the two, $F(2,42) = 3.85$, $p = .029$. Simple effects testing to explore this interaction showed that prime type had no significant effect at PCE latencies, $F(2,42) = 0.59$, $p = .559$, but had a significant effect at NCE latencies $F(2,42) = 6.25$, $p = .004$. Follow-up testing of the NCE data showed that Go primes produced a trend to fewer actions than neutral primes $t(21) = 1.58$, $p = .065$, while No-Go primes significantly increased the proportion of actions $t(21) = 2.39$, $p = .013$. Comparing the proportions for Go and No-Go primes directly showed that priming caused a significant 6.7% swing in ‘free’ choices $t(21) = 2.99$, $p = 003$.

3.5. Supplementary analyses

We performed two supplementary analyses to investigate specific concerns with our experimental design. Experiments 1 and 2 used left/right arrows. Effects of primes on motor inhibition are thus potentially confounded with spatial compatibility effects (Simon, 1969). Experiment 3 used up/down arrows, and so should avoid this confound. We therefore compared the effects of priming between Experiment 1 and the PCE data from Experiment 3, and between Experiment 2 and the NCE data from Experiment 3, using separate mixed model ANOVAs on the proportion of free-choice actions. If priming of motor inhibition strongly depends on spatial compatibility effects, these ANOVAs should reveal significant main effects of prime orientation. For PCE priming results, there was no significant main effects of either Prime or orientation, nor was there a significant interaction (all $p > .074$). For NCE priming results, there was a strong main effect of Prime type, $F(2,84) = 13.1$, $p < .001$, but no significant main effect of orientation and no interaction(both $p > .349$). This suggests that NCE priming effects are not merely spatial compatibility effects (e.g., Simon, 1969).

In a further analysis, we investigated whether the effects of primes on free-choice responses could involve a form of speed-accuracy trade-off. In particular, since, our design encouraged advance preparation of action. Therefore, a focus on speed might be expected to produce both rapid response times and few choices to inhibit, while a more conservative information-processing strategy might produce both slower response times and more choices to inhibit. In that case, the effect of each prime type on a participant’s response times should be strongly related to the effect of the same prime on the proportion of free-choice actions. To investigate this possibility, we correlated the effects of Go primes on each participant's free choice response times and action choices. A similar correlation was performed for NoGo primes. Neither correlation was significant (all $p > .1$).

Full *F*, *t* and difference values can be found in Supplementary Tables 11 and 12).

4. Discussion

These experiments provide the first evidence, to our knowledge, that unconscious priming can influence the 'free' decision to act or inhibit. We used a modified Go/No-Go paradigm in which Go, No-Go or Free Choice targets were preceded by masked primes. The primes were congruent with Go targets, No-Go targets, or were neutral. By varying the SOA between primes and targets, we were able to use the same prime stimulus to either facilitate or inhibit the response to the target. Subliminal primes were shown to influence both response times and action choices, in both forced and free choice conditions.

In particular, our subliminal primes were able to influence the intentional decision to withhold action on free-choice trials. A Go prime at NCE latency increased the proportion of choices to inhibit on free-choice trials, while No-Go primes increased the proportion of choices to act. This effect was consistent with previous NCE effects on forced choice reaction time, and with our own data. Briefly, the target-congruent prime acts to slow responses to the target, by a process of auto-inhibition of the target-related response (Eimer, 1999; Schlaghecken, Rowley, Sembi, Simmons, & Whitcomb, 2007), whilst target-incongruent primes speed this response. NCE effects are often explained in terms of auto-inhibitory processes induced by primes (Eimer & Schlaghecken, 1998). We show that these processes may also influence the 'free' decision to act or not. Intentional decisions to withhold action might arise for the same reason as auto-inhibition in NCE priming. That is, if internal action decisions are not subsequently confirmed and reinforced, the corresponding motor activation may then be suppressed. This process of auto-inhibition may partly explain why volitional decisions often appear weak and changeable (Fleming, Mars, Gladwin, & Haggard, 2009). Some authors argue that the NCE is due not to motor inhibition, but to interactions between prime and mask, leading to a perceptual after-effect. This effectively primes the opposite direction arrow from that shown as a prime (Lleras & Enns, 2004; Verleger et al., 2004). Our results cannot address this controversy directly. However, a significant body of experimental research (Boy, Husain, Singh, & Sumner, 2010; Schlaghecken & Eimer, 2006) has been presented in favour of the auto-inhibition account. Our core finding, that free decisions to inhibit can be unconsciously biased, stands independently of precise details of the mechanisms of NCE priming.

We found that PCE priming had no significant effect on free choice to act or inhibit. However, PCE priming did significantly modulate response times as expected, with Go primes speeding and No-Go primes slowing responses. That is, NCE priming influenced response choices, while PCE priming influenced response latencies. This interesting pattern of association was not predicted, and requires further research. Very speculatively, action choices may involve management of noise levels within action decision systems, and therefore be subject to NCEs. In contrast, PCEs may reflect excitability of post-decisional motor execution pathways, for example as measured by lateralised readiness potentials (Eimer & Schlaghecken, 1998). In previous research (Schlaghecken & Eimer, 2004), free choices of which of two action alternatives to perform were sensitive to both PCE and NCE priming effects. Our current results suggest that, when free choice concerns not which action to select, but instead concerns the later decision of whether to execute or inhibit the prepared action at the last moment (Brass & Haggard, 2008), facilitatory PCE priming effects are weaker than inhibitory NCE priming effects. This may reflect the importance of late-stage inhibition for free choices to act or not act.

Finally, Experiment 3, used up and down instead of left and right arrows as primes and targets, and compared PCE and NCE latencies in the same participants. Since the stimulus and response dimensions in Experiment 3 were orthogonal, these results exclude any spatial-compatibility explanations that could potentially be applied to Experiments 1 and 2 (i.e., compatibility between response hand and arrow direction producing a "Simon Effect", Simon, 1969). In Experiment 3 we again demonstrated unconscious priming effects on intentional inhibition, this time when automatic spatial stimulus–response mappings are eliminated. Moreover, comparisons between experiments showed that stimulus orientation did not significantly influence the size of priming effects Thus, priming of intentional inhibition is not simply a reflection of 'Simon inhibition' and spatial incompatibility costs. Experiment 3 also replicated using a within-subjects design, the different effects of PCE and NCE priming on response times and free choices to act or inhibit.

These results suggest that relatively late, volitional, high-level cognitive control processes can be manipulated by non-conscious means, contrary to previous supposition (Dehaene et al., 2003). Previous studies showed how non-conscious factors can influence volitional decisions, and indeed entire behavioural patterns. For example, "social priming" effects suggest that behaviour can be unconsciously cued by social stereotypes (Bargh, Chen, & Burrows, 1996). However, Doyen, Klein, Pichon, and Cleeremans (2012) could not replicate this result. Further, our paradigm has some experimental advantages over "social priming" methods: First, we explicitly demonstrated the subliminal nature of the priming stimuli. Second, we demonstrated bipolar directionality of the priming effects (that is, we show facilitatory and inhibitory primes in both PCE and NCE cases). Finally, we have been able to use a within-subjects design, which is not generally possible in social priming settings.

Low-level influences on high-level cognition have been widely studied. For example, voluntary task-choice can be affected by bottom-up influences such as task-difficulty or repetition of task-set (Lien & Ruthruff, 2008; Poljac & Yeung, 2012; Yeung, 2010). However, these studies appear to involve an earlier processing stage than intentional inhibition (Brass & Haggard, 2008). The psychological interest of our study arises from the combination of bottom-up influence, and the traditional association between consciousness, self-control, and the final inhibitory ''veto'' over one's own actions. Influential theories distinguish fully-conscious late-stage processes from early non-conscious representation (Dehaene et al., 2003). In contrast, our result suggests that the late-stage processes of action inhibition may also be subject to unconscious environmental influences.

Our experiment unconsciously manipulated a late-stage control process hile the individual remained unaware of the manipulation. Our participants' decisions to act or inhibit were presumably conscious, though we did not explicitly test for this, and indeed there is no established method for doing so. However, we can be confident that their (conscious) decisions depended on unconscious influences from the external environment.

Our results suggest, then, that inhibition of voluntary action is **not only** high-level and deliberate. Previous cognitive models viewed decisions to inhibit as interruption of routine schematised behaviour in novel situations, for example in the supervisory attentional system (Norman & Shallice, 1986; Shallice & Burgess, 1996). In the current paradigm, our subliminal prime manipulations may just bias ongoing fluctuating activation levels of different action alternatives (Leuthold & Kopp, 1998), and act as an additional driver of internal noise in action decision circuits. Such effects could therefore potentially be explained by a diffusion model (Schurger, Pereira, Treisman, & Cohen, 2009), combined with competitive inhibition between alternatives. Our results do not exclude hierarchical cognitive control of decisions to inhibit, but show that low-level influences also contribute.

We observed priming of free decisions to inhibit in the very constrained setting of a laboratory experimental paradigm. Subliminal priming effects are known to be paradigm-specific, and do not generalise to everyday behavioural control. Therefore, it remains unclear if the mechanisms we have demonstrated are important in the real world. However, our results have potentially interesting implications for self-control. The capacity to inhibit the impulse to act is of extreme legal importance. Our findings suggest that this capacity can be unconsciously influenced by external factors, at least under the restricted circumstances of our experiments. Since individuals are not aware of these factors, perhaps they cannot reasonably control them, and thus cannot be responsible for their own failures to inhibit? Our study also has a more positive implication: inhibitory capacity can be increased by unconscious influences. This raises the interesting possibility of training self-control using the techniques of implicit learning.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2013.11.005.

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