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Unconsciously Triggered Response Inhibition Requires An Executive Setting

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Abstract

Much research on response inhibition has focused on a consciously triggered variety (i.e. outright stopping of action). However, recent studies show that response inhibition can also be triggered unconsciously. For example, van Gaal, Ridderinkhof, Scholte, & Lamme (2010) showed that an unconscious No-go prime slowed down ongoing behavior, at least when outright stopping was sometimes required (i.e., in an executive setting). Here we replicated that result but also went further by including a condition with no executive setting. Now there was no slowing following a No-go prime. These results support the hypothesis that an executive setting is necessary for unconsciously triggered inhibition. We speculate that this arises from the fact that when the context includes outright stopping, the brain network for response inhibition is primed and it can be triggered by the unconscious prime. The result has theoretical implications for the distinction between conscious and unconscious response inhibition and also clinical implications for how to train response inhibition so that it is instantiated automatically.

Keywords

masked prime; go/nogo; automatic inhibition; stopping; learning

Introduction

Outright stopping is a form of top-down response inhibition typified by stop-signal and Go/No-go tasks (Verbruggen & Logan, 2008a; Chikazoe, 2010). However, two sets of studies have challenged the assumption that such response inhibition needs to be consciously triggered. First, response inhibition can become automatic after learning (e.g., Chiu, Aron, & Verbruggen, 2012; Lenartowicz, Verbruggen, Logan, & Poldrack, 2011; Verbruggen & Logan, 2008b), and secondly, response inhibition can be triggered unconsciously (e.g., van Gaal et al., 2008; van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009; van Gaal, Ridderinkhof, Scholte, & Lamme, 2010; van Gaal, Lamme, Fahrenfort, & Ridderinkhof, 2011). While both automatic and unconsciously triggered inhibition have been thought of as ‘bottom-up’ forms of inhibition, new evidence suggests that automatic inhibition may only emerge in an executive setting (where, for example, conflict resolution and top-down response inhibition is needed) (Chiu, Aron, & Verbruggen, 2012). Here we examined whether this is also the case for unconsciously triggered inhibition.

First, we briefly discuss the studies on ‘automatic inhibition’. These studies use a learning paradigm, consisting of a ‘training’ and a ‘test’ phase (e.g., Verbruggen & Logan, 2008b). In that particular study, participants were first trained to Nogo (not press a key) to living words

and Go (press a key) to non-living ones. Then, in the test phase, they were required to 'Go' to living words that previously were Nogo (i.e. nogo_then_go). The authors showed that RTs to nogo_then_go stimuli in the test phase were elongated compared to other conditions. They interpreted this RT-slowness as behavioral evidence for automatic inhibition. Specifically, it was proposed that the learning of the stimulus-stop association during training produced an inhibitory 'tag', which was subsequently retrieved in the test phase for nogo_then_go stimuli. Using a neurophysiological method, Chiu, Aron, & Verbruggen (2012) showed that the RT-slowness for such nogo_then_go stimuli in the test phase was accompanied by motor suppression at a mere 100 ms post-stimulus. Surprisingly, however, Chiu, Aron, Verbruggen (2012) did not observe motor suppression for items that were consistently associated with stopping (i.e. nogo in the late phase of training *and* in test), even though one would expect automatic inhibition to also occur for these. The authors explained this anomaly in the consistent condition on the view that items with an inhibition tag can only affect behavior if there is a current executive setting (e.g. a situation involving top down response inhibition, or task-level conflict). In that study, due to behavior automation after repeated stimulus-Go/No-go associations in the consistent condition, subjects probably experienced reduced task-level conflict, i.e., an absence of executive setting.

Given the speculation by Chiu, Aron, & Verbruggen (2012) that automatic inhibition only emerges in an executive setting, here we hypothesized that unconsciously triggered inhibition would also only occur in an executive setting. Studies of unconsciously triggered inhibition typically use a masked prime paradigm (e.g., van Gaal et al., 2008; van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009; van Gaal, Ridderinkhof, Scholte, & Lamme, 2010; van Gaal, Lamme, Fahrenfort, & Ridderinkhof, 2011). For example, van Gaal, Ridderinkhof, Scholte, & Lamme (2010) modified the traditional Go/No-go paradigm so that in some trials, No-go primes were presented very briefly (16.7 ms) and were followed by a contour mask (200 ms). This manipulation rendered the No-go prime invisible (i.e., discrimination accuracy was at chance). Thus, participants would mostly make a 'Go' response because the No-go prime was not consciously perceived. On trials with strongly masked No-go primes, Go RTs were prolonged, suggesting that response inhibition was triggered by unconsciously perceived No-go primes (van Gaal, Ridderinkhof, Scholte, & Lamme, 2010).

To test whether the RT-slowness finding by van Gaal and colleagues occurs because it is embedded in an executive setting (i.e., one where outright stopping is occasionally required), we adopted their Go/No-go masked priming paradigm, but in addition we included a 'Go-only' condition. In the Go/No-go condition, outright stopping is part of the task-set, and thus there is an executive setting. By contrast, in the Go-only condition, there is no executive setting. We expected to replicate van Gaal, Ridderinkhof, Scholte, & Lamme (2010)'s original finding of RT-slowness in the Go/No-go condition for the strongly masked No-go prime, and we also expected to show that this RT-slowness does not occur in the Go-only condition because there is no executive setting.

Experiment 1

Methods

Participants—Eighteen undergraduates (8 males) from the University of California San Diego participated for extra credit. All reported normal or corrected-to-normal visual acuity and provided written informed consent according to a local Institutional Review Board protocol. Data from two participants were excluded due to above-chance discrimination of the primes.

Apparatus and Stimuli—Stimuli were displayed by an iMac with a 20-in CRT monitor (60 Hz refresh rate). Participants viewed the display from a fixed distance of 68 cm and responded to the stimuli by pressing the ‘m’ key on the standard keyboard. Stimulus presentation and behavioral data collection were controlled using custom MATLAB code (The MathWorks, Natick, MA) and the Psychophysics Toolbox 3 (Brainard, 1997). We used the same stimulus parameters specified in van Gaal, Ridderinkhof, Scholte, & Lamme (2010).

Design and Procedure—The experiment included two conditions. The first condition was exactly the same as in van Gaal, Ridderinkhof, Scholte, & Lamme (2010), which was a Go/No-go task, requiring an executive setting. The second condition was a Go-only task, without an executive setting. All participants performed the two conditions in the same order, i.e. Go/No-go and then Go-only (Fig. 1C).

For the Go/No-go task, participants were instructed to respond to a white annulus as fast as possible. However, they needed to withhold the response if a visible ‘No-go’ prime preceded the annulus, else they continued to respond. There were two masking conditions in the Go/No-go task – strongly and weakly masked (240 trials each), which differ in the stimulus onset asynchrony (SOA) of the prime stimulus and the mask (see Fig. 1A & 1B). For both strongly and weakly masked condition, there was an equal number of trials with the Go and the No-go prime. However, participants were expected to make ‘Go’ responses on almost all trials with strongly masked primes because they could not discriminate the primes.

Following the Go/No-go task, with intermixed strongly and weakly masked conditions, participants performed the Go-only task, which included only the strongly masked condition. To ensure that the primes were not consciously perceived, and also to motivate participants’ attention to the briefly presented primes, two-alternative forced-choice discrimination questions were included at the end of 48 trials. Participants were told that they would Go (press ‘m’) for the annulus on every single trial, but then in some trials, a discrimination question would pop up and asked them which of the two shapes had been flashed before the annulus in the current trial. Participants would then press ‘v’ or ‘n’ to indicate perceiving either a square or a diamond (counterbalanced across participants).

Results

The key dependent variable was RT for strongly masked trials in the Go/No-go vs. Go-only task. We analyzed these RTs with an ANOVA with the factors of executive setting (Go/No-go vs. Go-only) and prime type (Go vs. No-go). As expected, this revealed a significant interaction between executive setting and prime type, $F(1,15) = 7.81, p < .05$, as well as significant main effects of executive setting, $F(1,15) = 12.59, p < .01$ and prime type, $F(1,15) = 18.23, p < .01$ (Fig. 2A).

Post-hoc *t*-tests revealed significant longer RTs following No-go primes than Go primes in the task with the executive setting, $t(15) = -4.52, p < .01$; but not in the task without the executive setting, $t(15) = -1.26, p = .23$. The former effect was not merely due to a few trials with longer RTs, as the entire distribution for No-go primes was shifted compared with that for Go primes whereas those were overlapping in the task without the executive setting (Fig. 2B).¹

¹We also performed *t*-tests on the percentage of trials for each RT bin of 100 ms. For the Go/No-go task, the greatest difference between the two distributions was in the middle bin of the distribution, i.e., 300–400 ms ($p = 0.04$, 1-tail, Bonferroni corrected), but not in the bins at the tail. There was no significant difference in any bin for the Go-only task (p 's $> .5$).

The accuracy of the forced-choice discrimination was at chance (51.9%, $SEM = 1.4$) and d-prime was not significantly different from zero (0.1, $SEM = .08$, $p > .5$), suggesting that the primes were not consciously perceived. However, to examine whether RT-slowness in the Go/No-go task was due to the visibility of No-go primes in a subset of participants, a correlation was performed between d-prime and RT-slowness (RTs for No-go vs. Go prime) for both tasks. No significant correlation was observed for either task (p 's $> .8$).

The commission error rate for the weakly masked No-go trials was 5 % ($SEM = 1.1$), suggesting that participants successfully performed response inhibition as instructed. For the weakly masked trials with the Go prime, participants were accurate (95%, $SEM = 2.3$) and fast (336 ms, $SEM = 10$).

Discussion

While some have argued that a putative executive function such as response inhibition is necessarily intentional (e.g., Kunde, Reuss, & Kiesel, 2012; Jack & Shallice, 2001), recent evidence suggests that response inhibition can also be triggered automatically (e.g., Verbruggen & Logan, 2009) and unconsciously (e.g., van Gaal et al., 2008; van Gaal, Ridderinkhof, Scholte, & Lamme, 2010). Here we qualify these observations by showing that unconscious response inhibition does occur, but only when there is an executive setting.

Using the masked prime paradigm of van Gaal, Ridderinkhof, Scholte, & Lamme (2010), we replicated their finding of RT-slowness following No-go primes in a Go/No-go task. Also, we went further by showing that No-go primes have no effect on RTs in a Go-only task. While both the Go/No-go task and the Go-only task involved detection of a signal, they differed in whether outright stopping was occasionally required. In the Go/No-go task, 2/3 of trials required a Go response. However, occasionally participants had to outright stop the prepotent Go response if the weakly masked No-go prime was presented. By contrast, the Go-only task did not require any outright stopping. We argue it is the critical requirement to occasionally perform outright response inhibition that confers an executive setting upon the Go/No-go task but not the Go-only one.

There are however other factors that could account for the lack of RT-slowness in the Go-only condition. First, perhaps there was insufficient learning of the stimulus-stop association in the Go/No-go task. To address this, we performed a second experiment with twice as many trials as Experiment 1. If the lack of RT-slowness in Experiment 1 was due to insufficient training, we should now observe more RT-slowness in Experiment 2 because participants received more training. Second, perhaps the subject did not pay attention to the screen when the prime was presented in the Go-only task, and thus the No-go prime had no chance to enter consciousness and to affect RTs (c.f., Leonard & Chiu, 2007). In Experiment 1, we included discrimination trials to motivate participants' attention. However, because the participants performed at chance (as the primes were strongly masked), it was difficult to infer whether participants had paid attention or not. In Experiment 2, we included an occasional attention probe (a red circle) to ensure that participants were paying attention at the time when the primes were presented in the Go-only task. While these probes were briefly presented (same as Go/No-go primes), they were not masked. Thus, participants should be able to detect them if their attention was oriented to the screen. If the lack of RT-slowness in Experiment 1 was merely due to a lack of attention, we should now observe RT-slowness in Experiment 2.

Experiment 2

Methods

Participants—Twenty undergraduates (9 males) from the University of California San Diego participated for extra credit. All reported normal or corrected-to-normal visual acuity and provided written informed consent. Data from two participants were excluded due to above-chance discrimination of the primes.

Apparatus and Stimuli—Same as Experiment 1.

Design and Procedure—Same as Experiment 1 with two modifications (Fig. 3A). First, participants performed two sets of the two tasks. Second, we included ‘attention probe’ trials in the Go-only task, during which a red circle (visual angle of 0.47°) was presented, and participants would press ‘g’ instead of ‘m’ as in other Go trials

Results

To examine learning, RTs for the strongly masked trials were analyzed with an ANOVA with the factors of executive setting (Go/No-go vs. Go-only), prime type (Go vs. No-go) and set (first set vs. second set). This revealed a significant two-way interaction between executive setting and prime type, $F(1,17) = 11.39, p < .01$, which is consistent with Experiment 1. Importantly, the three-way interaction was not significant, $F(1,17) = .10, p < .5$, showing that learning did not have an effect on the above interaction. Post-hoc t-tests revealed that there were significant RT-slowness in the Go/No-go task for both sets, p 's $< .05$, but there was no such slowing in the Go-only task for either set, p 's $> .5$ (Fig. 3B). Thus, this result excludes the possibility that the lack of RT-slowness in the Go-only task was merely due to insufficient learning.

To examine attention, we computed hits and false alarms for probe trials. Participants performed very well because the mean hit rate was high, (90%, $SEM = 3$) whereas the false alarm rate was very low, (0.3%, $SEM = .08$). This result suggested that the lack of RT-slowness in the Go-only task (Fig. 3B) could not be attributed to a lack of attention to the primes. Finally, the masking was again effective and the primes were not consciously perceived (0.1, $SEM = .11; p > .1$).

General Discussion

In two experiments, we replicated the finding of unconscious triggered inhibition in a Go/No-go task by van Gaal, Ridderinkhof, Scholte, & Lamme (2010). Furthermore, we showed no such effect in a Go-only task. In Experiment 2, we confirmed that this effect was not due to insufficient learning, or a lack of attention. Instead, we argue that it is the critical requirement to occasionally perform outright response inhibition that confers an executive setting upon the Go/No-go task but not the Go-only one.

The idea that ‘automatic’ or ‘unconscious’ processes require the presence of a particular task-set is consistent with other demonstrations of the importance of ‘goal-contingency’ for eliciting automatic or unconscious processes (Kunde, Reuss, & Kiesel, 2012; Hommel, 2007; Bargh & Ferguson, 2000; Verbruggen & Logan, 2009; Anderson & Folk, 2012²). For example, Verbruggen & Logan (2009) showed that the word ‘Stop’ did not have any effect

²Participants responded (Go) to red-colored targets but No-go if they were blue. The authors found that RTs to red targets were much slower if targets were among blue-colored flankers than others (i.e., red or green [a neutral color]). They explained this RT slowing as a ‘contingent involuntary motor inhibition’ because blue defined ‘No-go’ as part of the task goal. We suspect that ‘blue’ might acquire automatic inhibition in this task (but perhaps only in this task), as it was consistently associated with No-go.

on behavior if stopping was not relevant, but it did when stopping was relevant. Note that even though the word ‘Stop’ has a life-long association with stopping, it still did not slow RT if it was not relevant.

The neural mechanisms for automatic/unconscious inhibition likely relate to (parts of) the same brain network as conscious outright stopping. For outright stopping, many studies point to a predominantly right hemisphere network of brain regions including the inferior frontal gyrus, the pre-supplementary motor area and the basal ganglia, (e.g., Aron et al., 2007; Boehler et al., 2010; Chikazoe, 2010; Buchsbaum, Greer, Chang, & Berman, 2005; Chambers, Garavan, & Bellgrove, 2009; Swick, Ashley, & Turken, 2011; Verbruggen & Logan, 2008a; Wager et al., 2005). Interestingly, the right inferior frontal gyrus within this network was also active during ‘automatic inhibition’ (Lenartowicz, Verbruggen, Logan, & Poldrack, 2011) and ‘unconsciously triggered inhibition’ (van Gaal, Ridderinkhof, Scholte, & Lamme, 2010). Based on our results, we suggest that a masked No-go prime or stop signal only triggers this prefrontal cortical network for response inhibition if that brain network is already active, i.e. if the subject is in an executive setting, which presumably includes occasional outright stopping, task-switching (Monsell, 2003), or dealing with other kinds of response conflict such as flanker interference (Eriksen & Eriksen, 1974).

The requirement of an ‘executive setting’ for the manifestation of unconscious/automatic response inhibition has practical implications. For example, several studies have aimed to recruit these bottom-up forms of response inhibition to change motivated behavior (e.g., Houben, Nederkoorn, Wiers, & Jansen, 2011; Houben & Jansen, 2011; Veling & Aarts, 2009; 2011). In the study by Houben, Nederkoorn, Wiers, & Jansen (2011), heavy drinkers were trained to associate No-go with pictures of beer. Interestingly, they reported a reduction in weekly alcohol consumption subsequently. However, future studies need to investigate whether those effects indeed arise from automatic inhibition manifested at the motor level as in Chiu, Aron and Verbruggen (2012), or due to other purely cognitive (e.g. reappraisal) processes. If the former mechanism is at play, then our results suggest that long-term effects would be larger if participants are in an executive setting (e.g. thinking about, or preparing to, stop) during their day-to-day encounters with motivating stimuli.

In conclusion, we show that having an executive setting for outright stopping is a requirement for unconsciously triggered inhibition to emerge. This is consistent with the wider conceptualization that only ‘goal-contingent’ processes affect behavior. We suppose that a cortical network for outright stopping can be triggered to affect behavior by automatic/unconscious stimuli if that brain network is already active in the task context. Therefore, to recruit automatic or unconscious response inhibition for controlling motivated behavior (e.g., addiction), an executive setting might need to be in place at the time that these effects are desired.

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Figure 1. Example trials for the two masking conditions

(A) For weakly masked trials, the square (in this example) was presented for a long duration (233 ms) and the SOA between the square and the meta-contrast mask (white annulus) was also long (233 ms). Thus, participants could discriminate the shape (diamond vs. square). If the square was assigned to be the ‘No-go’ signal for this participant, s/he should withhold from making a response to the annulus. (B) By contrast, for strongly masked trials, the prime was presented only for 16.7 ms, and the SOA between the prime and the metacontrast mask was ~50 ms, which rendered the shape subliminal. This figure is a simplified version of van Gaal, Ridderinkhof, Scholte, & Lamme (2010)’s task figure. (C) The design of Experiment 1: the first part includes a Go/No-go task (a mix of Fig. 1A & B) requiring an executive setting and the second part includes only a Go task (Fig. 1B) without an executive setting.

Figure 2. Behavioral performance for task with and without executive setting
 (A) Mean response times ($\pm$ SEM). (B) Mean response time distributions ($\pm$ SEM) of strongly masked trials in the Go/No-go task (i.e., with executive setting) and Go-only task (i.e., without executive setting).

Figure 3. Design and data of Experiment 2
(A) Task design and example trials. Note that the red circle was colored gray here. (B) Mean response times ($\pm$ SEM) for two sets of Go/No-go, Go-only task as a function of prime types.