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Conditional Automaticity in Response Selection: Contingent Involuntary Response Inhibition With Varied Stimulus-Response Mapping

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Abstract

One aspect of effective cognitive control is the ability to withhold contextually inappropriate responses. The inhibition of a response can be elicited by a goal-relevant stop signal, which has been characterized as a voluntary cognitive process. Cases in which inhibition is triggered automatically by a stimulus have been reported but are limited to instances in which the withholding of a response is associated with the same stimulus over repeated trials, which reflects the gradual emergence of automaticity through associative learning. Findings such as these suggest that inhibitory control is driven by two dissociable mechanisms, one that is flexible but deliberate and another that is automatic but inflexibly learned. In the present study, we showed that response inhibition can be involuntarily triggered when stimulus-response mapping varies unpredictably, without contributions from associative learning. Our findings demonstrate that automatic response inhibition can be flexibly conditioned on top-down goals, which has broad implications for theories of cognitive control.

Keywords

inhibition, cognitive control, automaticity, response inhibition, cognition(s), selective attention

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Cognitive control refers to the set of processes that coordinates cognitive activity such that appropriate behavioral responses are made to goal-relevant stimuli. Effective control requires not only the selective perceptual processing of relevant stimuli, but also the ability to conduct, modify, and execute action plans in accordance with contextually appropriate stimulus-response mappings. The latter involves the selection and execution of goal-directed responses as well as the inhibition of responses that are inappropriate and may lead to unwanted outcomes.

On the perceptual side, there is growing consensus that cognitive control is accomplished through the establishment of a task-related top-down control setting that biases perceptual processing in favor of stimuli carrying properties consistent with that setting (Banich, 2009; Desimone & Duncan, 1995; Miller & Cohen, 2001), even when those stimuli are known to be irrelevant by virtue of other stimulus properties, such as location (Anderson & Folk, 2010; Folk, Remington, & Johnston, 1992; Wyble, Folk, & Potter, 2013). Thus, even the otherwise automatic, involuntary selection of highly salient stimuli can be conditional on top-down control settings (but see Theeuwes, 2010). Given evidence for similar effects in other processing domains (Bargh, 1989; Besner, Stoltz, & Boutilier, 1997; Smith, Besner, & Miyoshi, 1994), it is possible that this type of *conditional automaticity* represents a fundamental principle of executive control.

On the response side, however, the degree to which the automatic inhibition of irrelevant responses can be conditioned on top-down goals is less clear. Response inhibition has traditionally been investigated using paradigms in which the withholding of a motor response is

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elicited by a goal-relevant stimulus (e.g., Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003; Aron & Poldrack, 2006; Logan, 1983; Logan & Cowan, 1984; Verbruggen, Liefooghe, & Vandierendonck, 2004). Under such conditions, the observed response inhibition is required by the demands of the task, which leads to the conclusion that it reflects a voluntary act of cognitive control. However, more recent research suggests that response inhibition can proceed automatically as well, independently of voluntary control.

Stimuli consistently associated with the withholding of a motor response come to automatically elicit response inhibition, which interferes with later attempts to respond to such stimuli when task requirements change (Chiu, Aron, & Verbruggen, 2012; Lenartowicz, Verbruggen, Logan, & Poldrack, 2011; Verbruggen & Logan, 2008). Response inhibition can also be elicited by a subliminally presented stop signal (van Gaal, Ridderinkhof, Scholte, & Lamme, 2010; van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009), which suggests that response inhibition can proceed without conscious awareness. It is important to note, however, that even such unconsciously evoked response inhibition requires a currently active goal state in which participants are prepared to stop when the stop signal is perceived (Chiu & Aron, 2013).

Using a variant of the Eriksen flankers task (Eriksen & Eriksen, 1974), we previously provided preliminary evidence consistent with the idea that involuntary response inhibition can be contingent on the goal state of the observer (Anderson and Folk, 2012a). In that experiment, we asked participants to perform a go/no-go task in which they reported the identity of a centrally presented letter, but only if the letter was red; if the letter was blue, they were required to withhold their response. This target letter was flanked by other letters known to be irrelevant to the task, which were presented prior to the onset of the target. Participants were instructed to ignore these irrelevant flankers, which could either be compatible or incompatible with the response associated with the target. The results showed that when the flankers possessed the color of the no-go target, they selectively produced a reverse-compatibility effect indicative of the automatic inhibition of the response associated with stimuli possessing a no-go-related feature.

All prior studies investigating response inhibition have used consistent mapping, in which the requirement to withhold a response is consistently mapped onto a particular stimulus over many trials. Consistent mapping has long been known to facilitate the emergence of automatic processing that persists despite countermanding goals, whereas variable mapping requires deliberate and controlled goal-directed processing (e.g., Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Furthermore, the extent to which cognitive-control settings can be rapidly adjusted to guide selection under variable-mapping conditions remains controversial and debated (see Awh, Belopolsky, & Theeuwes, 2012, for some discussion on this issue). To date, there is no direct evidence for a mechanism of involuntary response inhibition that can be flexibly configured via the goal state of the observer and does not depend on the rigidly inflexible associative learning that develops under consistent-mapping conditions. Although the involuntary response inhibition we reported previously (Anderson and Folk, 2012a) might be explained as arising from automatic yet goal-contingent processing mechanisms, the use of consistent stimulus/no-response mapping makes it impossible to determine whether this is indeed the case. On the contrary, the current state of the literature suggests two dissociable mechanisms of inhibitory control, one that is flexible but deliberate and another that is automatic but so inflexible that it cannot be reconfigured when the task demands change (e.g., Chiu et al., 2012; Lenartowicz et al., 2011; Verbruggen & Logan, 2008).

In the present study, we directly tested whether contingent involuntary response inhibition can be observed under conditions of varied stimulus-response mapping. We had participants perform a go/no-go flankers task as in our previous research (Anderson and Folk, 2012a), except that the colors indicating go and no go varied unpredictably from trial to trial. Targets could be either red or blue, and a color-word cue at the beginning of each trial indicated which color would serve as the go color for that trial (and, by extension, which would serve as the no-go color). Thus, participants could instantiate a top-down set for which color would serve as the no-go color on a given trial, but this mapping of color to no-go response was inconsistent across trials. Of interest was whether the flankers in the no-go color would selectively produce a reverse-compatibility effect consistent with response inhibition in spite of the inconsistent mapping manipulation.

Experiment 1

Method

Participants. Fifteen Johns Hopkins University undergraduate students participated. All had normal or corrected-to-normal visual acuity and color vision, and all were compensated for their participation with course credit.

Apparatus. An Apple Mac Mini equipped with MATLAB software (The MathWorks, Natick, MA) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) was used to present the stimuli on an Asus (Fremont, CA) VE247 monitor. The participants viewed the monitor from a distance of approximately 50 cm in a dimly lit room. Manual responses were entered by participants using a standard keyboard.

Stimuli. Each trial involved four different displays (see Fig. 1). The first display consisted of a color-word cue presented in the center of the screen, rendered in bold 80-point Monaco font in all capital letters. Each letter was rendered in the color indicated by the word, which designated the color that would serve as the go color on that trial. In the second display, the fixation display, a white fixation cross (1.8° × 1.8° of visual angle) appeared following a blank interstimulus interval. The third display, the flanker display, consisted of two identical colored flankers (2.75° × 1.4°) presented 2.6° center-to-center to the left and right of the fixation cross. The flankers were either red or blue. In the fourth display, the target display, a target letter (2.75° × 1.4°) replaced the fixation cross at the center of the screen while the flankers remained on screen. The target was either red or blue. Each trial was followed by a blank intertrial interval (ITI). The letters used for the flankers and target were "A" and "X."

Design. The experiment consisted of five blocks of 96 trials each. Within each block, cue color, target color, target identity, flanker color, and flanker-target compatibility were fully crossed and counterbalanced, and trials were presented in a random order. Thus, 50% of the trials were go trials, and 50% were no-go trials.

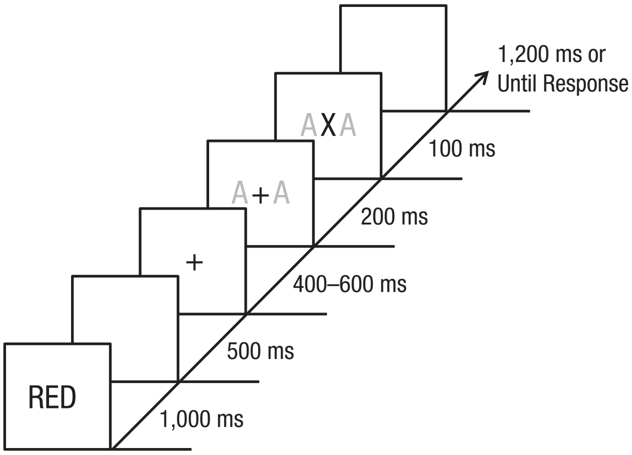

Fig. 1. Sequence and timing of events for a sample trial in Experiment 1. Each trial began with the presentation of a word cue presented in the same color that the word named; this cue designated the go color on that trial. (Note that the figure is rendered in gray scale, but the actual stimuli used in the experiment were colored red or blue.) This was followed by a blank screen, and then by the fixation display for a randomly varying period. Then two identical flankers ("A" or "X") were presented on either side of the fixation cross. Following the flanker display, the fixation cross was replaced with the target letter while the flankers remained on screen. Trials on which the cue and target were the same color were go trials; trials on which the cue and target were different colors were no-go trials. The screen then turned blank and waited until the participant pressed a key or 1,200 ms had elapsed, after which the trial timed out. Participants were instructed to indicate the target identity ("A" or "X") on go trials and to withhold response on no-go trials.

Procedure. Participants were instructed to respond as quickly as possible while minimizing errors and to respond only when the target color matched the cue color (go trials). Participants were also informed that the flankers were irrelevant to the task and did not predict the upcoming target, and that they should focus exclusively on preparing for the upcoming target when the flankers appeared.

Each trial began with the presentation of the color-word cue for 1,000 ms, followed by a 500-ms blank screen, and then by the fixation display for a randomly varying period of 400, 500, or 600 ms. After this period, two identical flankers were presented along with the fixation cross for 200 ms. Following the flanker display, the central fixation cross was replaced with the target letter while the flankers remained on screen for 100 ms. The screen then turned blank and waited until the participant responded or 1,200 ms had elapsed, after which the trial timed out. Each trial was followed by a blank ITI lasting 1,000 ms.

If the target color matched the cue color on that trial, participants were instructed to identify it as an "A" by pressing the "m" key and as an "X" by pressing the "z" key. If the target color did not match the cue color, they were instructed to withhold responding. False alarms (responses to no-go targets), misses (failing to respond to go targets), and incorrect responses to go targets were all considered errors. The computer emitted a 500-ms long, 1,000-Hz tone to inform the participant when an error occurred. The experiment began with 40 practice trials.

Results and discussion

Mean response time (RT) to correctly identify targets on go trials was entered in a 2 × 2 analysis of variance (ANOVA), with flanker color (go vs. no go) and flanker-target compatibility (compatible vs. incompatible) as within-subjects factors. This analysis revealed no significant main effects, flanker color: $F(1, 14) = 1.38$, $p = .260$; compatibility: $F < 1$. However, there was a significant interaction between flanker color and flanker-target compatibility, $F(1, 14) = 46.85$, $p < .001$, $\eta_p^2 = .770$ (Fig. 2). Planned comparisons indicated that flankers in the no-go color produced a significant reverse-compatibility effect, $t(14) = -3.54$, $p = .003$, $d = 0.91$, whereas flankers in the go color produced a positive compatibility effect, $t(14) = 2.32$, $p = .036$, $d = 0.60$.

The same ANOVA on accuracy (the percentage of correctly identified targets) revealed only a main effect of compatibility, $F(1, 14) = 4.61$, $p = .050$, $\eta_p^2 = .248$ (other Fs < 2.5, ps > .14), with the pattern mirroring the interaction in RTs for flankers in the go color (compatible: M = 94.9%, incompatible: M = 95.6%) and for flankers in the no-go color (compatible: M = 92.9%, incompatible:

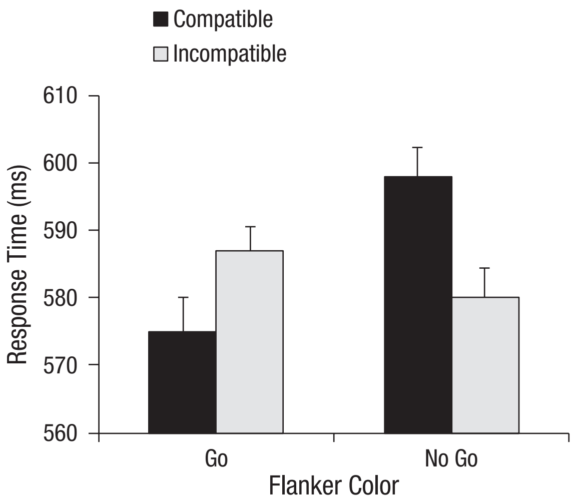

Fig. 2. Results from Experiment 1: mean response time on go trials as a function of flanker color (go vs. no go) and compatibility between flankers and the expected target response. Error bars show +1 within-subjects *SEM*.

M = 95.5%). False alarms and misses occurred very infrequently (*M*s = 0.8% and 1.1%, respectively). Despite the inconsistent mapping of color to no-go stimuli, flankers possessing the no-go color on a given trial produced a robust reverse-compatibility effect consistent with response inhibition, whereas flankers possessing the go color produced no evidence of inhibition and in fact produced a positive compatibility effect. This finding demonstrates involuntary response inhibition that is uniquely driven by flexibly configured goal-directed processing mechanisms.

Experiment 2

One alternative explanation for the reverse-compatibility effect observed in Experiment 1 is that participants may have inhibited the percept of the specific flanker letter rather than the response associated with it, which would make the target more difficult to perceive. It is also possible that this reverse-compatibility effect might be partially explained by slowing as a result of flanker-target identity grouping effects on compatible trials. To rule out these alternative explanations, and to replicate the critical result, we conducted a second experiment in which the flanker and target were never matched in letter identity by mapping two different letters to each response.

Method

Participants. Eighteen Johns Hopkins University undergraduate students participated. All had normal or corrected-to-normal visual acuity and color vision, and all were compensated with $10 for their participation.

Experimental task. The experimental task was identical to that of Experiment 1, with the following exceptions. Four different letters were used: "A," "B," "X," and "Y." On go trials, participants responded to "A" and "B" with the "z" key and to "X" and "Y" with the "m" key on the computer keyboard. On compatible trials, the flanker and target were always a different letter from the same response category. The experiment consisted of four blocks of 128 trials each.

Results and discussion

A 2 × 2 ANOVA on RTs for correctly identified targets on go trials with flanker color (go vs. no go) and flanker-target compatibility (compatible vs. incompatible) as within-subjects factors revealed a main effect of flanker color, $F(1, 17) = 5.77$, $p = .028$, $\eta_p^2 = .253$, but no main effect of compatibility ($F < 1$). However, we replicated the critical interaction, $F(1, 17) = 10.40$, $p = .005$, $\eta_p^2 = .380$ (Fig. 3). Planned comparisons indicated that flankers in the no-go color again produced a significant reverse-compatibility effect, $t(17) = -2.12$, $p = .049$, $d = 0.50$, whereas flankers in the go color produced a marginally significant positive compatibility effect, $t(17) = 2.02$, $p = .060$, $d = 0.48$. The same ANOVA on accuracy revealed no main effects or interaction for flankers in the go color (compatible: *M* = 93.8%, incompatible: *M* = 93.8%) and for flankers in the no-go color (compatible: *M* = 93.3%, incompatible: *M* = 92.6%; all *F*s < 1.1, *p*s > .32). False alarms and misses again occurred very infrequently (*M*s = 1.6% and 3.0%, respectively).

The results of Experiment 2 replicate those of Experiment 1, again demonstrating a reverse-compatibility

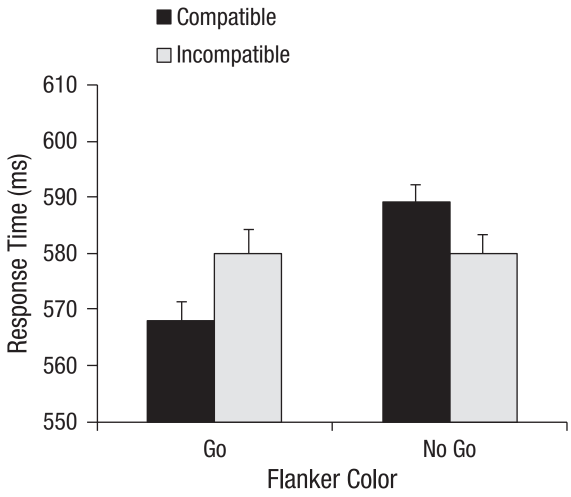

Fig. 3. Results from Experiment 2: mean response time on go trials as a function of flanker color (go vs. no go) and compatibility between flankers and the expected target response. Error bars show +1 within-subjects *SEM*.

effect selective to flankers matching the no-go color on a particular trial. This occurred even though the flankers and target were never matched in letter identity, which indicates that the observed inhibition was specific to the flanker-associated response.

Experiment 3

Another alternative explanation for the observed reverse-compatibility effects is that they were the result of flanker-target grouping by color and were independent of top-down control settings. When two differently colored stimuli are both associated with the same response, participants may experience conflict in responding to one without responding to the other. To definitively show that the observed reverse-compatibility effects were the result of cognitive-control settings, in Experiment 3, we eliminated the no-go component of the task. Flankers unpredictably matched or mismatched the target color, but participants always executed a response to the target regardless of its color.

Method

Participants. Sixteen Johns Hopkins University undergraduate students participated. All had normal or corrected-to-normal visual acuity and color vision, and all were compensated with $10 for their participation.

Experimental task. The experimental task was identical to that of Experiment 1, with the following exceptions. The cue display and subsequent blank interval were omitted on each trial, and participants responded regardless of the target color. An additional block of trials was also added, which resulted in six blocks of 96 trials each.

Results and discussion

Flanker color was broken down in terms of whether it matched or mismatched the subsequent target color on a given trial. A 2 × 2 ANOVA with flanker color (match vs. mismatch) and flanker-target compatibility (compatible vs. incompatible) as within-subjects factors revealed a main effect of compatibility, $F(1, 15) = 16.82$, $p = .001$, $\eta_p^2 = .529$, but no main effect of color ($F < 1$). There was again an interaction between color and compatibility, with the compatibility effect being larger when the flanker and target colors matched than when they did not, $F(1, 15) = 22.74$, $p < .001$, $\eta_p^2 = .603$ (Fig. 4). The pattern of results were quite different, however, in that the mismatching flankers now produced a positive compatibility effect, $t(15) = 2.60$, $p = .020$, $d = 0.65$. The same ANOVA on accuracy revealed a main effect of compatibility, $F(1, 15) = 6.12$, $p = .026$, $\eta_p^2 = .290$, and a marginally significant interaction between color and compatibility, $F(1, 15) = 4.27$, $p = .057$, $\eta_p^2 = .221$, which mirrored the pattern observed in RT for both the matching color (compatible: $M = 97.1\%$, incompatible: $M = 94.4\%$) and the mismatching color (compatible: $M = 95.8\%$, incompatible: $M = 95.1\%$; main effect of color: $F < 1$).

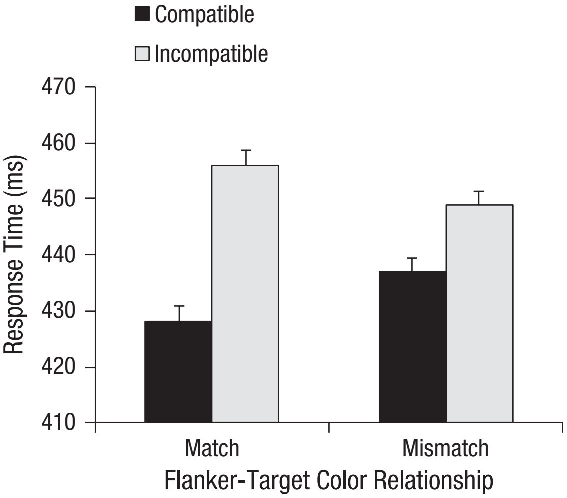

Fig. 4. Results from Experiment 3: mean response time as a function of whether the flanker color matched or mismatched the target color and compatibility between flankers and the expected target response. Error bars show +1 within-subjects *SEM*.

Experiment 3 demonstrates that when participants have the goal of responding to the target regardless of its color, irrelevant flankers activate an associated response regardless of whether their color winds up matching the subsequent target color. Thus, the findings of Experiment 3 are further consistent with the theory of contingent automaticity, mirroring the influence of top-down goals on perceptual processing under conditions of target-color uncertainty (Folk & Anderson, 2010). Strikingly, this experiment demonstrates that the reverse-compatibility effect observed in Experiments 1 and 2 depends on flexibly configured top-down control settings for withholding a response, which qualitatively change how the flanker is automatically processed. The observed interaction between flanker color and flanker-target compatibility also suggests that flankers rendered in a different color from the target are more efficiently ignored than flankers rendered in the same color as the target, which reflects a benefit of perceptual grouping by color.

General Discussion

It is well understood that response inhibition can be elicited by a task-relevant stimulus, consistent with voluntary cognitive control (e.g., Aron et al., 2003; Logan, 1983), and can also proceed automatically following the associative learning that accompanies consistent mapping between a stimulus and the need to stop or withhold a response (Chiu et al., 2012; Lenartowicz et al., 2011; Verbruggen & Logan, 2008). In the present study, we demonstrated that response inhibition can be elicited automatically by a stimulus without the ability to learn from consistent mapping, which reflects a learning-independent mechanism of automatically triggered inhibition contingent on top-down task set.

In Experiments 1 and 2, the observed inhibition of the response elicited by the flankers in the no-go color cannot be explained by an effect of voluntarily initiated response inhibition. If this reverse-compatibility effect merely reflected a voluntary strategy for inhibiting inappropriate flanker-associated responses, inhibition should have been observed for the flankers in the go color as well. Both color flankers were irrelevant to the task, and the identity of the flankers was just as likely to be compatible with the subsequent target as it was to be incompatible. Thus, participants had equal incentive to ignore the flankers regardless of their color. The fact that the observed inhibition was selective to the flankers in the no-go color suggests that it arose specifically as an involuntary consequence of a top-down set to inhibit responses triggered by stimuli of a particular color (see also Anderson & Folk, 2012a).

The observed inhibition also cannot be explained by negative priming caused by the cue color, as the no-go color was itself never cued. Rather, by cuing the go color, we ensured that participants could prepare for which color would consequently serve as the no-go color. Experiment 3 demonstrates that the reverse-compatibility effect elicited by flankers in the no-go color is not a pure function of the mismatch in color between the go target and the flankers and instead critically depends on the goal state of the observer. Nor can the observed reverse-compatibility effect in Experiments 1 and 2 be explained by a carryover of inhibition from the target in the no-go color on the previous trial, as this color was equally likely to serve as the go or no-go color on the subsequent trial. The selectivity of the observed reverse-compatibility effect was uniquely consistent with an involuntary consequence of a goal-directed strategy; participants prepared to inhibit the response associated with a target in the no-go color, and this inhibition was automatically applied to any stimulus possessing the no-go feature.

Using a spatial-cuing paradigm that employed a similar go/no-go design in which the go and no-go target color varied unpredictably across trials, Belopolsky, Schreij, and Theeuwes (2010) demonstrated that cues carrying the no-go color on a given trial produced a negative cuing effect consistent with the location-specific inhibition of the cued location. One interpretation of this perceptual-level inhibition is that it reflects the involuntary consequence of an inhibitory strategy adopted by participants (e.g., Anderson & Folk, 2012b; Sawaki & Luck, 2010). The present findings provide parallel evidence for such automatic goal-driven inhibition in the domain of response selection.

A recent topic of debate has been the extent to which cognitive-control settings for guiding selection can be rapidly adjusted to reflect trial-by-trial changes in task contingencies (Awh et al., 2012). In experiments involving consistently defined targets, contingency-based effects on selection might be explained by goal-independent processes, such as priming, or the development of habitual responding. Demonstrations that the ability to restrict perceptual processing to a target-defining feature can fail when that feature varies from trial to trial (e.g., Belopolsky et al., 2010; although see Lien, Ruthruff, & Johnston, 2010) have led to the hypothesis that top-down control may be limited to voluntary postselection processing (Theeuwes, 2010). Using a variable-mapping procedure, we showed that top-down control settings can be adjusted on a trial-by-trial level to exert automatic control over response selection, which provides evidence that cognitive-control processes can be rapidly recruited to involuntarily bias information processing.

The locus of the inhibition observed in the present study is unclear. One possibility is that the flankers evoked a motor response signal in our task, and the observed inhibition occurred at the level of response execution. This reflects the sort of inhibition that occurs in response to a stop signal (e.g., Aron et al., 2003; Aron & Poldrack, 2006; Logan, 1983; Logan & Cowan, 1984). Another possibility is that flankers in the no-go color automatically activated a rule for withholding their associated response, which inhibited the subsequent selection of that response following processing of the target. Additional research, likely measuring or manipulating neural activity in the motor system, will be required to determine the specific locus of the inhibition observed in the present study. In any case, our findings support the idea that response rules can be automatically applied purely as a function of the flexibly configured goal state of the observer, which has far-reaching implications for understanding the cognitive mechanisms underlying inhibitory control.

The present study demonstrates inhibitory cognitive control that is simultaneously flexible and automatic. Such inhibition contrasts with what is known to develop under consistent mapping conditions through associative learning (Chiu et al., 2012; Lenartowicz et al., 2011; Verbruggen & Logan, 2008). We have shown that preparation to automatically inhibit a response can be flexibly configured at the level of a single trial. Our findings suggest that goal-directed inhibitory control may not be as voluntary, effortful, and controlled a process as previously thought. We showed that the ability to reflexively inhibit a particular response can be controlled with the same flexibility as voluntary and deliberate executive functions, bypassing the need for the associative learning that unfolds over much longer time frames while allowing for rapid adjustment based on changing demands. More generally, the contingent involuntary inhibition of a response identified in the present study provides further evidence that conditional automaticity represents a general principle of executive functioning that applies not only to perceptual processing but also to response selection.

Author Contributions

B. A. Anderson and C. L. Folk developed the study concept. B. A. Anderson designed the experiment. B. A. Anderson collected and analyzed the data. B. A. Anderson and C. L. Folk wrote the manuscript.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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