

Multiple Systems for Cognitive Control: Evidence From a Hybrid Prime-Simon Task

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Cognitive control resolves conflicts between appropriate and inappropriate response tendencies. Is this achieved by a unitary all-purpose conflict control system, or do independent subsystems deal with different aspects of conflicting information? In a fully factorial hybrid prime-Simon task, participants responded to the identity of targets displayed at different nominally irrelevant screen locations, preceded by nominally irrelevant, consciously or nonconsciously perceived primes. The response required by the target's identity could match or mismatch (a) the target's location, and (b) the prime's identity, resulting in potential conflict (a) across and (b) within stimulus domains. Conflict effects were investigated within and across trials. Results suggest that (i) nonconsciously perceived information elicits within-trial control, but—unlike consciously perceived information—no across-trial behavioral modulation; (ii) separate subsystems deal with conflicts arising from different stimulus domains; and (iii) occasional apparent interactions between domains reflect a particular difficulty in reactivating a just-discarded response (reactivation aversion effect, RAE).

Keywords: cognitive control, masked priming, negative compatibility effect, Simon effect, Gratton effect, hybrid task

How the brain controls its own processes, adjusting the organism's ongoing behavior to the ever-changing demands of the environment, is one of the central questions in cognitive neuroscience. Successful behavior means being able to give the most appropriate response to the most relevant—but not necessarily most salient—environmental events. How these are selected is typically studied in response conflict paradigms, where response-relevant (target) and response-irrelevant (distractor) information are systematically combined. On some trials, relevant and irrelevant information are both associated with the same motor response, resulting in converging response activation. On others, they are associated with different responses, resulting in a response conflict. To the extent that distractor-related processes interfere with the selection and execution of the correct response, reaction times will be longer and error rates higher on conflict relative to nonconflict trials. The magnitude of these interference effects thus provides an estimate for the effectiveness of cognitive control: the smaller the interference from conflicting information, the more effective the control process. Consequently, factors that alter the magnitude of interference effects are regarded as factors affecting cognitive control.

Cognitive Control and Conflict Adaptation

A factor of particular relevance is the presence or absence of conflict on the immediately preceding trial. Following a conflict trial, interference effects are typically much smaller than following a nonconflict trial ("Gratton effect"), suggesting that after a conflict has been encountered, the impact of irrelevant information on the motor system is reduced (e.g., Gratton, Coles, & Donchin, 1992; Stürmer, Siggelkow, Dengler, & Leuthold, 2000; Wühr & Ansorge, 2005). According to *associative priming* accounts (e.g., Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laury, 2003; Nieuwenhuis et al., 2006), the Gratton effect reflects behavioral benefits of identical trial repetitions (i.e., faster responses and fewer errors when a nonconflict trial has been preceded by the identical nonconflict trial, and when a conflict trial has been preceded by the identical conflict trial; but see, e.g., Akcay & Hazeltine, 2007; Kerns et al., 2004; Ullsperger, Bylsma, & Botvinick, 2005, for Gratton effects in the absence of trial repetitions).

In contrast, the *conflict monitoring* account (e.g., Botvinick, Cohen, & Carter, 2004; Carter et al., 1998) holds that Gratton effects reflect the operation of a central control unit, situated in the prefrontal cortex, which monitors activity within the motor system and generates a top-down signal when competing response alternatives are simultaneously active. As a result, attention is focused more narrowly on those perceptual representations relevant to the current goal. In its original form, this model assumes that the central controller has no information about the source of a motor activation. Consequently, it cannot tailor its output to affect only a specific type of irrelevant information: it is *domain general* in the sense that any motor conflict—regardless of its origin—will cause a top-down modulation that biases all information processing away from all irrelevant environmental events.

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There is, however, increasing evidence that cognitive control acts, in fact, specifically rather than generally. For instance, in task-switching paradigms Gratton effects have been observed when the task or the task-relevant feature repeat, but not when they switch (e.g., Kiesel, Kunde, & Hoffmann, 2006; Notebaert & Verguts, 2008), suggesting that following a conflict, information processing is biased away from the irrelevant information present in that particular trial, not from all potential irrelevant information. The same pattern is observed even when the task remains constant and only the conflict-inducing domain alternates between trials (Funes, Lupianez, & Humphreys, 2010a, 2010b). Larger-scale conflict adaptation effects beyond the immediate trial context have similarly been found to be specific rather than general. For instance, selectively altering the proportion of conflict trials for one type of trial but not another leads to correspondingly selective modulation of behavioral effects (item-specific proportion congruency effect, e.g., Jacoby, Lindsay, & Hessels, 2003, and task-specific proportion congruency effects, e.g., Fernandez-Duque & Knight, 2008).¹ Findings like these have led to the development of hybrid conflict control models, which combine conflict monitoring and associative learning accounts (e.g., Blais, Robidoux, Risko, & Besner, 2007; Davelaar & Stevens, 2009; Verguts & Notebaert, 2008, 2009).

However, studies like those mentioned above, using different tasks or different types of conflicting information on different trials, might systematically overestimate the domain-specificity of cognitive control, as any domain-general effects might be obscured by confounding factors like task-switching costs (cf. Egner, 2008). In fact, contrasting evidence—domain-general conflict adaptation effects in task switching—has been observed across a variety of tasks (Freitas, Bahar, Yang, & Banai, 2007). A more conclusive test of domain-specific cognitive control would require a paradigm that combines different sources of conflict within each individual trial in a fully factorial design, such that levels of conflict within each source can be varied (a) independently from each other, and (b) without concomitant changes in task set, attentional demands, and so forth. Few studies to date have employed such a paradigm, and from those that have, the evidence again is mixed. For instance, while Egner, Delano, and Hirsch (2007) observed strictly domain-specific conflict adaptation, others have found evidence for domain-general cognitive control (e.g., Boy, Husain, & Sumner, 2010; Kunde & Wühr, 2006).

Evidence for Both Domain-Specific and Domain-General Control?

Kunde and Wühr (2006; Exp. 2) used a hybrid priming-Simon paradigm, where a target stimulus (a left- or right-pointing arrow requiring a left- or right-hand response), presented on the left- or right-hand side of the computer screen, was preceded by an identical or opposite-pointing arrow prime. On each trial, both sources of response-irrelevant information—target location and prime identity—were independently varied to either conflict with the response required by the target, or not. Results supported a domain-general account of cognitive control: within each trial, location-based (Simon) and shape-based (priming) effects interacted, such that Simon effects were reduced on trials with prime-induced conflict (or correspondingly, priming effects were reduced on trials with location-induced conflict). Furthermore, location-induced conflict was found to elicit (Gratton-) modulation of

Simon effects as well as of priming effects—however, the reverse was not true.

Using a similar design, Boy et al. (2010) studied the impact of nonconsciously perceived conflict on within-trial interactions and the Gratton effect. They employed a hybrid masked priming-flanker paradigm, where primes were presented centrally and were subsequently masked to render them unavailable to conscious awareness. They were then followed by a target accompanied by flanking stimuli (arrows pointing either in the same or opposite direction to the target). It was found that while the previous trial's flanker congruency did not modulate priming effects on the current trial (i.e., no domain-general Gratton effect, supporting domain specificity), the current trial's flanker congruency did (i.e., within-trial interactions, suggesting a domain-general mechanism). Interestingly, though, the latter was only the case under conditions where masked-prime induced activation was inhibited, not under conditions where inhibition was prevented. This led the authors to conclude that within-trial inhibitory control is shared across domains and independent of conscious awareness, whereas Gratton effects reflect an additional (possibly domain-specific) mechanism requiring conscious conflict awareness.

For both studies, however, alternative explanations seem possible. In Kunde and Wühr (2006), primes were presented at the same lateral position as the subsequent target, such that on each trial not only the target location, but also the prime location was congruent (not in conflict) or incongruent (conflicting) with respect to the required response. Logically, this “prime congruency” might have been responsible for the within-trial interactions and the seeming domain-general Gratton effect on priming. Similarly, in Boy et al. (2010), the two sources of irrelevant information (primes and flankers), as well as the relevant information, were all from the same domain (i.e., stimulus shape: left- or right-pointing arrows). Thus while Kunde and Wühr might have obtained spurious evidence for domain-general Gratton effects because primes carried not only shape but also location information, Boy et al. (2010) might have obtained spurious domain-general within-trial effects because all irrelevant stimuli carried the same shape information.

The Present Experiments

We aim to address these issues by employing a fully factorial hybrid two-source interference paradigm. Specifically, like Kunde and Wühr (2006), we used a hybrid prime-Simon task, with prime shape and target location as the two sources of potentially conflicting information. Unlike Kunde and Wühr, however, we always presented primes centrally (i.e., primes did not carry additional task-irrelevant location information). Furthermore, in each experiment half of the participants performed the prime-Simon task with nonmasked primes, whereas the other half performed the task with masked primes. The masked-prime procedure was similar to the one that Boy et al. (2010) employed to elicit low-level response inhibition. We also included neutral baseline conditions (nonarrow primes in Experiment 1, centrally presented targets in Experiment

¹ Note, however, that Funes et al. (2010b) report a domain-general proportion congruency effect.

2) in order to better assess the extent of within-trial interactions and between-trial Gratton effects.²

First, we expect to obtain Simon effects in the form of faster and more accurate responses when target- and response-location coincide (location-congruent trials) than when they are in conflict (location-incongruent trials; Rubichi, Nicoletti, Umiltà, & Zorzi, 2000; Stürmer et al., 2000; Wühr & Ansorge, 2005). Second, with nonmasked primes, we expect responses to be faster and more accurate when prime and target converge on the same response (prime-compatible trial) than when they are associated with conflicting responses (prime-incompatible trial), resulting in a positive compatibility effect (PCE; Eimer & Schlaghecken, 2002; Kopp, Rist, & Mattler, 1996). Third, with masked primes, we expect the opposite pattern, that is, faster and more accurate responses with incompatible than with compatible primes (e.g., Boy et al., 2010; Eimer & Schlaghecken, 1998; Schlaghecken & Eimer, 2006). The question of interest is whether Simon and priming effects show evidence of domain-general cognitive control processes by (a) interacting with each other within each trial, and/or (b) triggering cross-domain Gratton effects from one trial to the next. If the results reported by Kunde and Wühr (2006) and by Boy et al. (2010) reflect genuine domain-general cognitive control mechanisms, we expect to find within-trial interactions of prime identity and target location with nonmasked as well as with masked primes. Furthermore, if between-trial conflict adaptation is domain general but requires conscious awareness of the conflict-inducing stimulus, we expect both domain-specific (prime-prime and location-location) and domain-general (prime-location and location-prime) Gratton effects with nonmasked primes, whereas with masked primes, we expect only location-based Gratton effects, but no prime-induced Gratton effects.

Experiments 1 and 2: Hybrid Prime-Simon Paradigm

The aim of the following experiments was to investigate whether or not Simon effects and priming effects (nonmasked or masked) interact in a hybrid prime-Simon paradigm both within a given trial (indicating common mechanisms for online conflict control) and between trials (indicating common mechanisms for behavioral adjustments following conflict vs. nonconflict trials). The crucial comparison for this type of analysis is between pairs of trials (e.g., comparing reaction times on conflict trials following a conflict trial with reaction times on conflict trials following a nonconflict trial). With two sources of conflict (prime identity and target location) and two levels of conflict in each (compatible/incompatible primes, and congruent/incongruent target locations), four individual trial types result, which—as each type of trial can follow a trial of the same type or any of the others—combine to produce 16 possible trial pairs. Including neutral baselines for each source of conflict (i.e., neutral primes and centrally presented targets) would increase the number of conflict levels in each source to three (compatible/neutral/incompatible primes, and congruent/central/incongruent target locations), correspondingly resulting in nine individual trial types, which would combine to produce 81 possible pairs. As it does not seem reasonable to include this many different conditions in one experiment, we decided to employ the prime and target baselines in two separate experiments. Experiment 1 thus used only two prime conditions (compatible and incompatible primes), but three target conditions (congruent, central, and incongruent targets). Corre-

spondingly, Experiment 2 used three prime conditions (compatible, neutral, and incompatible primes), but only two target conditions (congruent and incongruent targets). In all other respects, the two experiments were identical.

Method

Participants. Eighty volunteers (40 in each of the two experiments) participated for either course credit or payment of £6. Participants were aged 19–42 years ($M = 22.4$), and 35 were male. According to self-report, all but 10 participants were right-handed, and all had normal or corrected-to-normal vision. Half of the participants in each experiment were assigned to the “no mask” condition, and half to the “mask” condition. One participant from the no-mask condition of Experiment 2 was excluded from analysis due to excessive error rates (>30%).

Stimuli and apparatus. Left- and right-pointing double arrows (« and ») served as prime stimuli, subtending a visual angle of approximately $0.9^\circ \times 0.5^\circ$. In Experiment 2, a double plus sign (++) was employed as an additional neutral prime stimulus. In the “mask” conditions, primes were followed by a backward-masking stimulus to reduce prime visibility. Each mask was constructed on the basis of a virtual 9×9 matrix, randomly filled with overlapping horizontal, vertical and oblique lines of different lengths, resulting in a roughly rectangular array of approximately $2.5^\circ \times 1.0^\circ$. A new random mask was created on each trial in order to avoid perceptual learning of the mask and correspondingly increased prime identification (Schlaghecken, Blagrove, & Maylor, 2008; Schubö, Schlaghecken, & Meinecke, 2001). In the “no mask” conditions, an empty frame stimulus was presented instead of the mask, with a line thickness of 3 pixels and a size of approximately $2.5^\circ \times 1.0^\circ$ (i.e., the same size as the mask). All stimuli were presented in black on a white background on a 17-inch computer screen.

Procedure. Participants were seated in a dimly lit, sound attenuated chamber in front of a computer screen (viewing distance = 1.2 m), with response buttons under their left and right index fingers. The experiments comprised 12 blocks of 72 trials each, preceded by one practice block (24 trials). As depicted in Figure 1a, each trial began with a prime, presented for 33 ms,³ immediately followed by either a mask or the frame (presented for 100 ms), followed by a blank screen (100 ms). Next, a target was

² Note that without baselines, it is not possible to distinguish whether a given effect reflects a slowing of responses due to interference from conflicting activation, a speeding-up of responses due to facilitation from converging activation, or both. Consequently, it is equally impossible to interpret a change in effect size (within-trial interactions or Gratton effects) with any certainty.

³ A prime duration of 33 ms has been shown to produce NCEs more reliably than a 17-ms duration, presumably because 33-ms primes have a stronger impact on the visuomotor system, while still being effectively masked with scrambled-pattern backward masking (e.g., Schlaghecken, Rowley, Sembi, Simmons, & Whitcomb, 2007). To confirm this for the present set-up, we tested 12 additional volunteers (4 male; ages 18–23 years, $M = 19.3$) in a staircase-based prime identification experiment (similar to the procedure described in Eimer & Schlaghecken, 2002). Mean identification threshold was 38.7 ms, which did not differ significantly from 33 ms, $t(11) = 1.78$, $p > .1$. Furthermore, for both 17- and 33-ms primes, identification did not differ from chance accuracy (50%), $t < 1$.

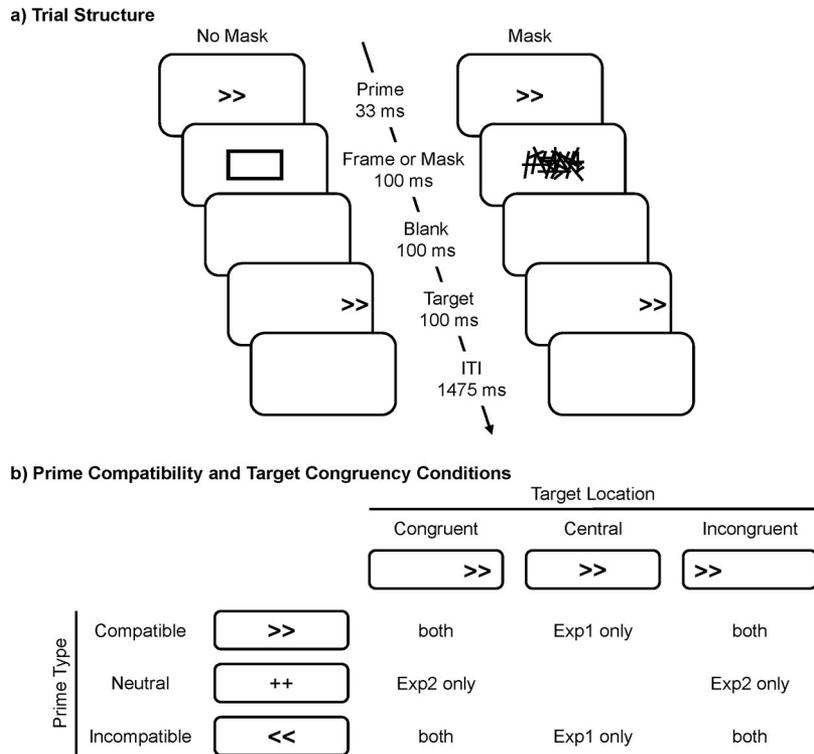


Figure 1. a) Schematic depiction of trial structure and masking conditions in Experiments 1 and 2 (the example depicts the compatible-prime congruent-target condition). Note that both experiments employed the no mask and the mask condition (between-subjects). b) Combination of all prime-compatibility and target-congruency conditions in Experiments 1 and 2. Note that while both experiments contained the four standard conditions (Compatible/Incompatible \times Congruent/Incongruent), only Experiment 1 contained (compatible or incompatible) central-target trials, and only Experiment 2 contained neutral-prime congruent and incongruent trials.

displayed for 100 ms. Intertrial-Interval (ITI) was 1475 ms. Primes, masks and frames were presented in the center of the screen. In Experiment 1, targets were presented randomly and with equal probability at fixation, 8.8° to the left of fixation, or 8.8° to the right. In Experiment 2, targets were presented randomly and with equal probability 8.8° to the left or right of fixation. Participants were instructed to maintain central eye fixation and to respond as quickly and accurately as possible to the direction of the target arrows (i.e., a left-hand key-press to arrows pointing to the left, and a right-hand key-press to arrows pointing to the right), regardless of target location.

Here, and in the remainder of this article, the term “compatibility” will be used to refer to the relationship between the prime’s and the target’s identity within a given trial, whereas the term “congruency” will be used to refer to the relationship between the target’s identity and its location on the screen (see Figure 1b). Trials were termed *compatible* when prime and target arrows pointed in the same direction, *incompatible* when they pointed in opposite directions, and *neutral* when the prime was a plus sign. Trials where target direction and target location corresponded (e.g., a left-pointing arrow appearing to the left of fixation) were termed *congruent* trials, trials where they were in conflict (e.g., a left-pointing arrow appearing to the right of fixation) were termed *incongruent* trials, and trials where targets were presented at fixation were termed *central-target* trials.

All trials (2 prime compatibility levels \times 3 target congruency levels \times 2 responses in Experiment 1, and 3 prime compatibility levels \times 2 target congruency levels \times 2 responses in Experiment 2) were presented randomly and with equal probability throughout each block, whereas masking condition (no mask vs. mask) was a between-subjects factor in both experiments.

Data analysis. Trials were grouped according to prime compatibility and target congruency, resulting in six trial types in each experiment (2 prime compatibility conditions \times 3 target congruency conditions in Experiment 1, and 3 prime compatibility conditions \times 2 target congruency conditions in Experiment 2). Sequential analyses were conducted for reaction times (RTs) only. Mean RTs were calculated separately for each of the 36 trial pairings (6 previous trial types \times 6 current trial types). Only RTs of correct responses following a correct response were taken into account. Because splitting the data into 36 combinations resulted in several almost completely error-free combinations, error analyses were conducted for within-trial effects only (i.e., on the six different basic types in each experiment, without taking sequential effects into account).

Data were analyzed using repeated measures analyses of variance (ANOVAs) with the between-subjects factor masking condition (no mask, mask), and the within-subject factors prime compatibility, target congruency, and (for RTs only) previous-trial compatibility and previous-trial congruency. Follow-up analyses

were conducted in the form of paired *t* tests, comparing the conditions of interest averaged across all subconditions (e.g., testing Simon effects by comparing RTs on congruent and incongruent trials, averaged across all priming and previous-trial conditions). In all analyses, Greenhouse-Geisser correction to the degrees of freedom was applied where appropriate, and corrected *p* values are reported. All tests were two-tailed, except where explicitly stated otherwise.

Results

Error rates. Mean RTs and error rates for the nonmasked and masked conditions in Experiments 1 and 2 are depicted in Figure 2, showing that error rates generally followed the same pattern as RTs (i.e., high error rates where RTs were long, low error rates where they were short), confirming that results did not reflect speed-accuracy trade-offs. Simon effects (higher error rates on incongruent than on congruent or central-target trials) were significant under both masking conditions in both experiments, all *F*s > 11.32, all *p*s < .001. Nonmasked primes produced PCEs (higher error rates on incompatible than on compatible or neutral prime trials), which were significant in Experiment 2, *F*(2, 36) = 3.29, *p* = .007, though not in Experiment 1, *F* < 1.4, *p* > .2. Masked primes produced NCEs (higher error rates on compatible than on incompatible or neutral prime trials) in both experiments, both *F*s > 17.95, both *p*s < .001.

Reaction Times

Mean RTs for each trial type—irrespective of preceding trial—are depicted in Figure 2. Sequential modulations of priming and Simon effects (e.g., RT difference between compatible and incompatible trials, plotted separately for trials following a compatible or an incompatible trial, etc.) are shown in Figure 3. Statistical results

of the omnibus ANOVAs for the two experiments are listed in Table 1. In the following, numbers in square brackets refer to the numbering of statistical comparisons in this table.

I. Main factors. In Experiment 1 (central-target baseline, no neutral primes), though not in Experiment 2 (neutral-prime baseline, but no central targets), RTs were shorter with masked than with nonmasked primes [1]. As expected, prime compatibility interacted with masking condition [2b], as nonmasked and masked primes produced effects of opposite polarity. In contrast, effects of target congruency [3a] were unaffected by the presence or absence of a mask [3b]. Follow-up analyses confirmed for both experiments significant PCEs with nonmasked primes, both *t*s > 2.11, both *p*s < .049, significant NCEs with masked primes, both *t*s > 6.88, both *p*s < .001, and significant target congruency (Simon) effects in each masking condition, all *t*s > 6.03, all *p*s < .001.

The effects of the previous trial’s prime compatibility and target congruency mirrored these results. The previous trial’s prime compatibility interacted with masking condition, as with nonmasked primes, RTs were generally shorter following a compatible-prime trial, whereas with masked primes, they were shorter following an incompatible-prime trial [4b]. In contrast, RTs were generally shorter following a congruent than following an incongruent trial regardless of masking condition [5a].

II. Within-trial interactions. With nonmasked primes, Simon effects (RT difference between incongruent- and congruent-target trials) were larger when primes were compatible than when they were incompatible, whereas with masked primes, Simon effects appeared to be unaffected by prime compatibility. This pattern was reflected in a significant interaction between prime compatibility and target congruency, modulated by the mask factor, in Experiment 2 [6a,b], but failed to reach statistical significance in Experiment 1.

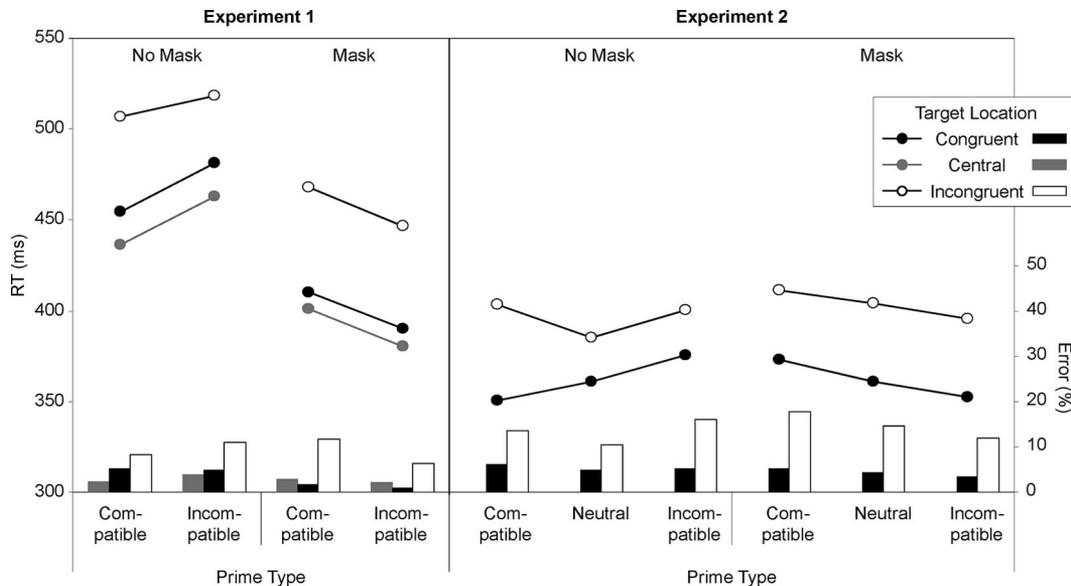


Figure 2. Mean Reaction Times (RTs in milliseconds; line graphs) and Error Rates (in percent; bar graphs) in the No Mask and Mask conditions of Experiments 1 and 2, plotted separately for compatible, neutral and incompatible prime trials, and for congruent (black), central (gray), and incongruent (white) target locations.

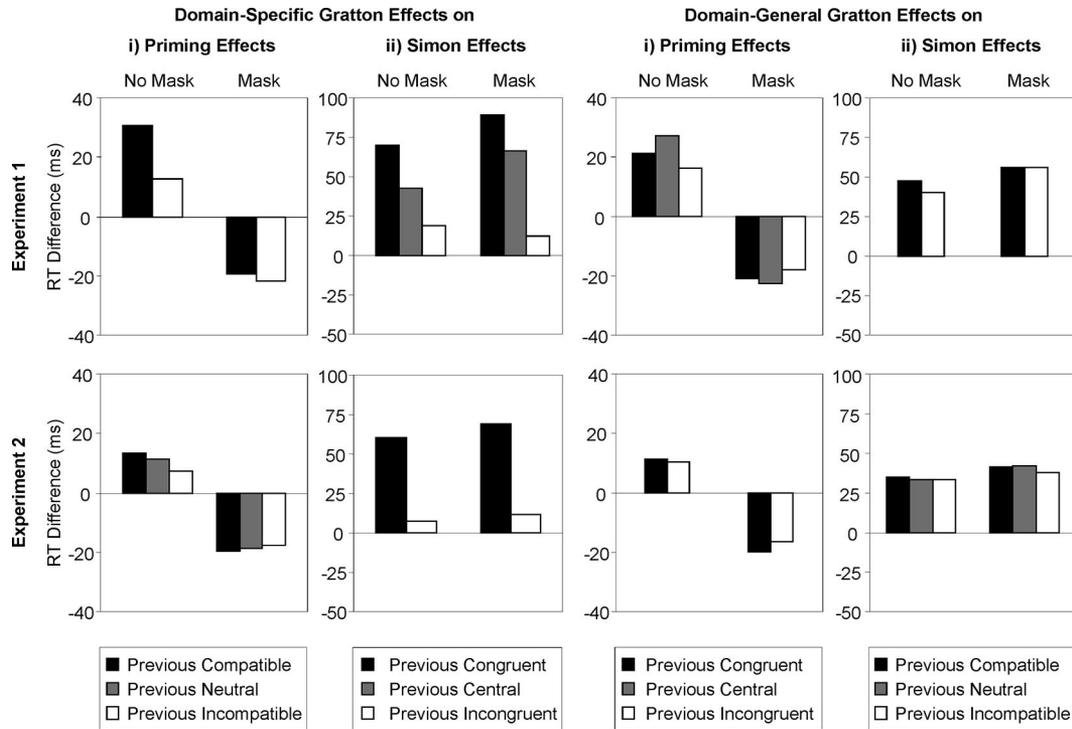


Figure 3. Effects of the previous trial's prime compatibility or target congruency on priming effects (incompatible RT minus compatible RT) and Simon effects (incongruent RT minus congruent RT). Panels on the left-hand side show domain-specific Gratton effects (i.e., priming effects as a function of the previous trial's prime compatibility, and Simon effects as a function of the previous trial's target congruency). Panels on the right-hand side show domain-general Gratton effects (i.e., priming effects as a function of the previous trial's target congruency, and Simon effects as a function of the previous trial's prime compatibility). Top row: Experiment 1; bottom row: Experiment 2.

However, inspection of Figure 2 suggests that the interaction in the nonmasked condition was driven exclusively by the disproportionately slow responses on trials with a compatible prime and an incongruent target. Follow-up analyses confirmed this observation. We compared priming and Simon effects on “interaction” trials (containing both an arrow prime and a laterally presented target) with baseline trials, which either (in Experiment 1) contained an arrow prime but a nonlateral (central) target, or (in Experiment 2) contained a lateral target but a nonarrow (neutral) prime. Comparison of priming effects on congruent, incongruent, and central-target trials in Experiment 1 revealed that while priming effects tended to be smaller on incongruent than on central-target trials, $t(19) = 1.93, p = .068$, they were indistinguishable between congruent and central-target trials, $t < 1$. Comparison of Simon effects on compatible, incompatible, and neutral-prime trials in Experiment 2 produced corresponding results: Simon effects were larger on compatible than on neutral-prime trials, $t(18) = 6.32, p < .001$, but virtually identical on incompatible and neutral-prime trials, $t < 1$.

III. Domain-specific Gratton effects (see left-hand side of Figure 3). In Experiment 1, priming effects were more positive following a compatible trial, and more negative following an incompatible trial, and this effect was much more pronounced with nonmasked than with masked primes [8a,b]. Although Figure 3 suggests that for nonmasked primes results are similar in Experiment 2, this experiment did not yield a statistically significant

domain-specific Gratton effect for primes. Follow-up analyses, comparing priming effects following compatible versus incompatible trials, confirmed the overall picture: with nonmasked primes, PCEs following compatible trials were approximately twice as large as PCEs following incompatible trials, and this difference was significant in Experiment 1 (30.8 vs. 12.5 ms), $t(19) = 5.39, p < .001$, but not in Experiment 2 (13.5 vs. 7.6 ms), $t(18) = 1.67, p = .11$. With masked primes, on the other hand, no domain-specific Gratton effect of prime compatibility was observed (Experiment 1: -19.2 vs. -21.8 ms; Experiment 2: -19.4 vs. -17.3 ms; both $t_s < 1$).

Furthermore, in both experiments Simon effects were largest following congruent-target trials, and smallest following incongruent-target trials [9a]. In Experiment 1, this effect was more pronounced with masked than with nonmasked primes [9b]; however, paired t tests, comparing Simon effects following congruent versus following incongruent trials, confirmed highly significant Gratton effects for target congruency with masked as well as nonmasked primes in both experiments (all $t_s > 5.61$, all $p_s < .001$).

IV. Domain-general Gratton effects (right-hand side of Figure 3). Overall, there were no significant effects of the previous trial's target congruency on the magnitude of the current trial's priming effects, or of the previous trial's prime compatibility on the magnitude of the current trial's Simon effect [10a–11b]. The only exception is the significant three-way interaction Current

Table 1

Statistical Results of Omnibus ANOVAs for RTs in Experiments 1 and 2, With One Between-Subject Factor (Mask) and Four Within-Subject Factors (Prime, Target, PPrime, PTarget)

Effect	Experiment 1			Experiment 2		
	<i>df</i>	<i>F</i>	<i>p</i>	<i>df</i>	<i>F</i>	<i>p</i>
1. Mask	1, 38	5.62	.02	1, 37	0.06	.80
I. Main effect prime compatibility						
2a. Prime	1, 38	0.03	.87	2, 74	4.92	.02
2b. Prime * Mask	1, 38	35.56	.00	2, 74	25.10	.00
I. Main effect target congruency						
3a. Target	2, 76	114.76	.00	1, 37	127.73	.00
3b. Target * Mask	2, 76	0.91	.39	1, 37	0.98	.33
I. Main effect previous prime compatibility						
4a. PPrime	1, 38	0.00	.96	2, 74	2.83	.07
4b. PPrime * Mask	1, 38	20.50	.00	2, 74	6.94	.00
I. Main effect previous target congruency						
5a. PTarget	2, 76	32.78	.00	1, 37	82.80	.00
5b. PTarget * Mask	2, 76	7.35	.00	1, 37	0.85	.36
II. Within-trial interactions						
6a. Prime * Target	2, 76	2.71	.08	2, 74	14.51	.00
6b. Prime * Target * Mask	2, 76	1.93	.16	2, 74	29.06	.00
7a. PPrime * PTarget	2, 76	0.57	.56	2, 74	1.43	.25
7b. PPrime * PTarget * Mask	2, 76	1.83	.17	2, 74	0.30	.72
III. Domain-specific Gratton effects: Prime compatibility						
8a. Prime * PPrime	1, 38	21.94	.00	4, 148	1.60	.19
8b. Prime * PPrime * Mask	1, 38	12.48	.00	4, 148	1.02	.39
III. Domain-specific Gratton effects: Target congruency						
9a. Target * PTarget	4, 152	81.11	.00	1, 37	110.82	.00
9b. Target * PTarget * Mask	4, 152	5.26	.00	1, 37	0.18	.67
IV. Domain-general Gratton effects						
10a. Prime * PTarget	2, 76	0.66	.51	2, 74	1.01	.37
10b. Prime * PTarget * Mask	2, 76	3.72	.03	2, 74	0.67	.52
11a. Target * PPrime	2, 76	1.35	.26	2, 74	0.90	.38
11b. Target * PPrime * Mask	2, 76	0.89	.40	2, 74	0.43	.57
V. Other						
12a. Prime * PPrime * PTarget	2, 76	0.74	.47	4, 148	0.35	.77
12b. Prime * PPrime * PTarget * Mask	2, 76	0.14	.86	4, 148	0.97	.40
13a. Target * PPrime * PTarget	4, 152	0.77	.53	2, 74	0.80	.44
13b. Target * PPrime * PTarget * Mask	4, 152	1.23	.30	2, 74	0.18	.80
14a. Prime * Target * PPrime	2, 76	0.18	.83	4, 148	0.85	.49
14b. Prime * Target * PPrime * Mask	2, 76	0.05	.95	4, 148	0.74	.55
15a. Prime * Target * PTarget	4, 152	1.55	.20	2, 74	8.13	.00
15b. Prime * Target * PTarget * Mask	4, 152	1.02	.39	2, 74	1.27	.28
16a. Prime * Target * PPrime * PTarget	4, 152	0.66	.60	4, 148	1.35	.26
16b. Prime * Target * PPrime * PTarget * Mask	4, 152	1.01	.40	4, 148	1.88	.13

Note. Between-subject factor: Mask (nonmasked, masked). Four within-subject factors: Prime (prime compatibility on the current trial); Target (target congruency on the current trial); PPrime (prime compatibility on the previous trial); and PTarget (target congruency on the previous trial). Bold typeface highlights significant effects.

Prime \times Previous Target \times Mask in Experiment 1 [10b]. However, inspection of Figure 3 suggests that this interaction—rather than reflecting a domain-general Gratton effect of previous target congruency on current prime compatibility effects—might be mostly driven by the fact that priming effects following central-target trials were larger than priming effects following either congruent or incongruent trials (i.e., the nonmasked prime PCE was more positive and the masked-prime NCE more negative following central targets than following laterally presented targets). In order to explore this possibility, ANOVAs without trials following central targets were conducted separately for each masking condition in Experiment 1. Results confirmed that when trials following central targets are omitted, the Current Prime \times Previ-

ous Target interaction disappeared in both masking conditions, both *F*s < 1.64, both *ps* > .21.

V. Other. The only remaining statistically significant result is a three-way interaction between current prime compatibility, current target congruency, and previous target congruency in Experiment 2 [15a]. This interaction reflects the fact that the increased Simon effect with compatible trials relative to neutral and incompatible trials (see Section II above) is present only following congruent trials (77.3, 61.4, and 56.4 ms for compatible, neutral, and incompatible trials, respectively), but not following incongruent trials (12.6, 4.1, and 11.4 ms). This was confirmed by follow-up *t* tests, comparing the magnitude of Simon effects on compatible trials with the magnitude of Simon effects on neutral

and on incompatible trials (collapsed across masking conditions, $df = 38$). For trials following congruent trials, both comparisons showed significant differences, both $t_s > 3.50$, both $p_s < .001$, whereas following incongruent trials, neither difference reached statistical significance, both $t_s < 1.83$, both $p_s > .075$.

General Discussion

The present results strongly support the notion that cognitive control of response conflict—whether high-level and top-down or low-level inhibitory—operates in a strictly domain-specific way. Most important, they show that apparent within-trial interactions between different sources of conflict do not reflect domain-general cognitive control, but merely a difficulty in reactivating a response that has just been discarded, and that conflicts at the motor stage do not always trigger Gratton effects. However, before discussing each of the findings, the conflict processing and different sources of conflict used in the present study should be considered in more detail.

Activation and Inhibition in Motor Priming and Simon Tasks

In motor priming, the shape of the response-irrelevant prime stimulus is assumed to partially activate its corresponding motor response simply because the link between shape and response is so sensitive that motor activation begins before the response-irrelevance of the prime has been fully appreciated (e.g., Neumann, 1990; Neumann & Klotz, 1994). Thus motor priming effects are assumed to reflect processes within the same, task-specific, S-R system. In the Simon task, in contrast, effects are thought to result from concurrent activation within two separate routes of motor control: one fast and automatic route activated by stimulus location, and a slow and controlled route processing stimulus identity (e.g., de Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990; for a detailed overview, see Proctor & Vu, 2006).

Once activated, task-irrelevant motor responses need to be inhibited in order to minimize their interference with correct response execution (e.g., Burle, Possamai, Vidal, Bonnet, & Hasbroucq, 2002; Ridderinkhof, 2002; for an alternative view, see, e.g., Hommel, 1994). Neurophysiological evidence suggests that the same fronto-cortical-subcortical network that mediates conflict detection and subsequent control processes is involved in online inhibitory conflict resolution (e.g., Cope, Georgious, Bradshaw, Ianssek, & Phillips, 1996; Liu, Banich, Jacobson, & Tanabe, 2004; Peterson et al., 2002; for reviews, see, e.g., Faw, 2003; Mansouri, Tanaka, & Buckley, 2009).

However, this seems to be true only when participants are consciously aware of the conflict-inducing stimuli. When a conflict is triggered by a subliminally presented stimulus (i.e., by a stimulus of which participants have no subjective conscious awareness, and which they cannot identify with more than chance accuracy), inhibition appears to be mediated by structures other than the prefrontal cortex. Specifically, it is assumed that the NCE observed with masked primes reflects a low-level “emergency brake” mechanism, which ensures that the initial prime-induced preactivation is quickly suppressed when sensory evidence supporting it is suddenly removed (e.g., Eimer & Schlaghecken, 1998;

Praamstra & Seiss, 2005; for alternative accounts of the NCE, see, e.g., Jaśkowski, 2007; Jaśkowski & Przekoracka-Krawczyk, 2005; Lleras & Enns, 2006). Evidence from fMRI (Aron et al., 2003) and patient studies (Sumner et al., 2007) suggests that this inhibition process is mediated by the supplementary motor area (SMA) in conjunction with the caudate nucleus, rather than by the prefrontal structures involved in supraliminal conflict tasks. Nonetheless, although motor preactivation and control processes in the masked prime paradigm occur outside the participant’s conscious awareness, they are still strictly in line with the participant’s current intentions (e.g., Ansorge & Neumann, 2005; Klapp & Haas, 2005; Schlaghecken & Eimer, 2004), even if these intentions themselves are not explicitly represented (Schlaghecken, Blagrove, & Maylor, 2007). This suggests that despite different underlying mechanisms, a close link exists between apparently “voluntary” and apparently “nonvoluntary” control processes. In the following, we will discuss how these various control processes affect performance in the hybrid prime-Simon task.

I. In a hybrid prime-Simon task with nonmasked and masked primes, prime compatibility and target congruency produce the expected interference effects (PCEs with nonmasked primes, NCEs with masked primes, and Simon effects). These show most clearly as immediate effects on the current trial, but—in a considerably weaker form—also as lasting effects on the subsequent trial. It would seem that the most parsimonious explanation for these lasting effects is that they do not reflect true priming or Simon effects (i.e., stimulus-specific effects on the behavior of the subsequent trial), but merely response adaptation effects (i.e., response speed effects on the response speed of the subsequent trial): responses are generally slightly faster following a fast response, and are generally slightly slower following a slow response, irrespective of any other factors (e.g., Laming, 1979).⁴ In this respect, these apparent lasting effects might bear some similarity to the increased response times in the nonmasked condition of Experiment 1: if targets potentially appear in the center (as they did in Experiment 1), then centrally presented nonmasked primes can easily be confused with the targets. Participants might therefore adopt a more cautious response approach, reflected in longer RTs, irrespective of any specific prime- or mask-related effects.

II. Statistical interactions between prime compatibility and target congruency, observed with nonmasked, but not with masked primes, are due to disproportionate slowing on trials where a compatible prime was followed by an incongruent target. At a first glance, the overall pattern seems to suggest that control processes operating on consciously perceived stimuli—whether the identity of a nonmasked prime or the location of a clearly visible target—share a common neural basis, whereas control processes operating on nonconsciously perceived stimuli are mediated by different structures (see also Kunde, 2003). However, closer examination of the prime compatibility-target congruency interaction casts doubt on this interpretation. Comparison with baseline trials (containing central targets or neutral primes)

⁴ Note that in line with this reasoning, the ratio of Simon effect size to absolute priming effect size (43.5 : 17.8 ms, ratio = 2.44) was about the same as the ratio of lasting target congruency to lasting prime compatibility effect size (9.3 : 4.4 ms, ratio = 2.11).

indicated that the interaction was driven by one data point only, namely, the disproportionately slow responses on compatible incongruent trials. On all other trials, prime compatibility and target congruency showed purely additive effects. The feature that distinguishes compatible incongruent trials from all other types of trials is that they entail a sequence of alternating response activations. Consider the case of a prime arrow pointing to the right, triggering a right-hand activation (R). On a compatible trial, the target arrow will also point to the right, requiring a right-hand response. If this trial is incongruent, this means that the target appears on the left side of the screen, which will trigger a left-hand activation (L), resulting in a sequence of alternating motor activations: $R_{(\text{prime identity-triggered})} \rightarrow L_{(\text{target location-triggered})} \rightarrow R_{(\text{target identity-triggered})}$. Importantly, no other type of trial shows such a sequence, where a response is initially activated, then discarded in favor of its opposite, and finally has to be reactivated (the other sequences for a right-pointing prime are: compatible congruent: $R \rightarrow R \rightarrow R$; incompatible congruent: $R \rightarrow L \rightarrow L$; and incompatible incongruent: $R \rightarrow R \rightarrow L$). We propose that the reactivation of a just-discarded response is particularly difficult and accounts for the seeming prime compatibility-target congruency interaction observed in the present study.

Such a “reactivation aversion” effect (RAE) is reminiscent of other inhibitory aftereffects, where responding to previously processed and then discarded information has been found to be impaired relative to responding to new information. Well-known examples include the negative priming phenomenon (e.g., Tipper, 1985, 2001), inhibition of return (e.g., Maylor & Hockey, 1985; Posner, Rafal, Choate, & Vaughan, 1985), repetition blindness (e.g., Kanwisher, 1987), task-set inhibition (Monsell, 2003), and the Ranschburg effect (e.g., Jahnke, 1969). Furthermore, within the specific context of motor activation and inhibition processes, Hoffman, Kiesel, and Sebald (2003) have reported an inhibitory aftereffect of nogo trials on subsequent responses to identical go trials, Rieger and Gauggel (1999) observed similar effects in a stop-signal paradigm, and Machado, Wyatt, Devine, and Knight (2007) found that at very long (>600 ms) distractor-target intervals, nonmasked distractor stimuli elicited an NCE-like effect. At a conceptual level, each of these phenomena can be described as a particular difficulty in accessing a pattern of neural activity (e.g., a stimulus representation or motor event) that has been activated recently, has then been de-activated, and now needs to be activated again. It would be interesting for future research to delineate the similarities and differences between these various effects, and to investigate whether RAEs reflect a general property of the nervous system, observable at different levels of complexity and within different time-scales, from very fast (~ 100 ms) at lower levels (reflected, for instance, in the NCE with masked primes) to very slow (>1000 ms) at higher levels (e.g., negative priming).

III. Domain-specific Gratton effects are readily observed for target congruency, are present—though less pronounced—for prime compatibility with nonmasked primes, but are absent for prime compatibility with masked primes. These findings replicate earlier results (e.g., Boy et al., 2010; Kunde, 2003; Kunde & Wühr, 2006) and confirm the hypothesis that for conflict-driven behavioral adjustments to occur, the conflict must have been consciously perceived. This fits with the assumption that such adjustments are initiated by control structures in the frontal lobes, and that only consciously perceived

stimuli are processed sufficiently to activate these structures (e.g., Dehaene et al., 2003; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene & Naccache, 2001; but see also Lau & Passingham, 2007).⁵

It is worth noting that in the present experiments, PCEs with nonmasked, consciously perceived primes were of approximately the same magnitude as NCEs with masked, nonconsciously perceived primes.⁶ This indicates that the lack of Gratton effects with masked primes is not due to nonconsciously triggered effects simply being weaker than consciously triggered effects and causing less motor conflict, an explanation which could, for instance, account for the results reported in Kunde (2003) or Dehaene et al. (2003). In the present experiment, motor conflicts elicited by nonmasked and masked stimuli were of equivalent magnitude, yet one produced a Gratton effect, while the other did not. If behavioral adjustments occurred whenever the monitoring system detected a conflict at the motor response stage, then this result would be difficult to explain. Why should the system’s ability to detect two simultaneously active motor responses depend on whether or not the stimuli giving rise to these responses were consciously perceived? The present result does not rule out the possibility that response conflict might be a critical signal for behavioral adjustments to be triggered. It does, however, strongly suggest that it is not the conflict at execution stages common to all motor outputs (i.e., primary motor cortex and supplementary motor area) that plays this role.⁷ This conclusion fits in with the final observation from the present study:

IV. Domain-general Gratton effects appear to be absent.

That is, even supraliminal, consciously perceived stimuli (non-masked primes and target locations) did not produce any discernable behavioral adjustments outside their own domain: following a trial with an incompatible (nonmasked) prime, priming effects were reduced, but Simon effects were unaffected, and following a trial with an incongruent target location, Simon effects were reduced, but priming effects were unaffected.

⁵ Note also that Klapp (2007), who reports proportion-congruency effects for subliminal primes, interprets these not as evidence for high-level control, but as low-level effects “mimicking” a conscious strategy.

⁶ Intuitively, one would expect that interference from a clearly visible prime is harder to overcome than interference from a subliminal prime, and that consequently PCEs should be substantially larger than NCEs. This pattern has in fact been observed in an earlier study (Eimer & Schlaghecken, 2002), but only when both prime and target were presented centrally, without any intervening stimulus (Exp. 1). When a nonmasking stimulus was presented between prime and target (Exp. 2), PCEs and NCEs were of similar magnitude, suggesting that presentation of an intervening stimulus—even if it does not reduce prime visibility—makes ignoring the prime easier, thus reducing interference effects.

⁷ In an implicit motor-sequence learning task, Ursu, Clark, Aizenstein, Stanger, and Carter (2009) found that sequence violations of which participants were not consciously aware nevertheless caused enhanced activity in the caudal ACC, consistent with the assumption that this structure monitors response conflict at late execution stages, independent of awareness. However, in this study, all stimuli were clearly visible and available to conscious awareness—that is, even though participants could not verbalize the conflict, it was not induced subliminally, and thus might well have been processed in the same way and by the same structures as other supraliminally presented stimuli.

Together, the absence of both a within-trial interaction of prime compatibility effects and target congruency effects (Section II) and domain-general Gratton effects (Section IV) strongly supports the notion that cognitive control is not mediated by a unitary system. These results complement findings from studies using hybrid interference paradigms (e.g., Egnér et al., 2007; Wendt, Kluwe, & Peters, 2006), task switching paradigms (e.g., Fernandez-Duque & Knight, 2008; Kiesel et al., 2006; Notebaert & Verguts, 2008), and “conflict-switching” paradigms (e.g., Funes et al., 2010a, 2010b), and suggest that the domain-general effects observed by Kunde and Wühr (2006) and Boy et al. (2010) were driven by the fact that in both of these studies, the two sources of potentially conflicting information came from the same domain (stimulus location in Kunde and Wühr, and stimulus shape in Boy et al.).

It has been suggested repeatedly that supraliminal conflict processing involves top-down reentry connections from prefrontal areas to perceptual cortical areas (e.g., Dehaene et al., 2003, 2006; Dehaene & Naccache, 2001). It seems tempting to assume that such top-down connections are domain specific at least to the extent that they involve anatomically distinct feature detectors (e.g., visual cortical neurons involved in processing shape information vs. neurons involved in processing location information vs. neurons involved in processing color information, etc.). If this hypothesis is correct, then whether or not domain-general Gratton effects will be observed in a hybrid task might be a matter of feature overlap between the two interference tasks: If there is no overlap (e.g., shape information and location information, as in the present experiments), no domain-general Gratton effects should occur. In contrast, if both sources of interference rely on the same feature (e.g., shape information in the form of a prime, and shape information in the form of flankers, or location information for both the prime and the target), then pseudo domain-general effects might be observed (for a related discussion, see, e.g., Funes et al., 2010a, 2010b).⁸

Finally, it is interesting to note that in a visual subliminal priming task, Wolbers et al. (2006) observed a tight functional coupling of pre-SMA with lateral occipital cortex and putamen—that is, with structures involved in visual perceptual processing and low-level response selection—under high-conflict conditions. This might be taken as evidence that cognitive control is never instantiated by one specific structure, but always comprises complex networks reflecting the specific task characteristics and situational demands.

⁸ It should be noted, however, that the present study differed from traditional Simon experiments in two respects. First, the target stimuli themselves had a left-right spatial asymmetry (arrow-heads being wide on one side and narrow on the other). Second, because primes were presented centrally, subsequently presented lateral targets might have induced a corresponding apparent motion. According to the feature overlap model (Kornblum et al., 1990; Proctor & Vu, 2006), this means that in addition to the S-R congruency of target location and response hand, there is an additional conceptual S-S congruency of stimulus shape and stimulus location, as well as an additional S-R congruency of induced motion and response hand. Either of these might have contributed to the observed Simon effects. However, this does not affect the conclusion drawn from the present results because for each of these additional factors, a domain-general control account would similarly predict within-trial interactions of priming and (shape- or motion-based) Simon effects as well as between-

trial cross-domain Gratton effects, and the absence of such effects supports a domain-specific account.

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