

# When Awareness Gets in the Way: Reactivation Aversion Effects Resolve the Generality/Specificity Paradox in Sensorimotor Interference Tasks

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Interference tasks combining different distractor types usually find that between-trial adaptations (congruency sequence effects [CSEs]) do not interact with each other, suggesting that sensorimotor control is domain-specific. However, within each trial, different distractor types often do interact, suggesting that control is domain-general. The present study presents a solution to this apparent paradox. In 3 experiments, testing 130 participants in total, we (a) confirm the simultaneous presence of between-trial domain-specific (noninteracting) CSEs and within-trial “domain-general” interactions in a fully factorial hybrid prime-Simon design free of repetition or contingency confounds; (b) demonstrate that the within-trial interaction occurs with supraliminal, but not with subliminal primes; and (c) show that it is disproportionately enlarged in older adults. Our findings suggest that whereas interference (priming and Simon) effects and CSEs reflect direct sensorimotor control, the within-trial interaction does not reflect sensorimotor control but “confusion” at higher-level processing stages (reactivation aversion effect [RAE]).

**Keywords:** sensorimotor interference paradox, hybrid prime-Simon task, congruency sequence effects, subliminal priming, aging

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A moth might have no choice but to circle the light but we, as humans, are generally able to inhibit a prepotent but detrimental action in favor of one better suited to our current goals—at least to some extent. Though vastly superior to that of an insect, our sensorimotor inhibitory control is far from perfect. We pick up the coffee instead of the phone, turn left toward home instead of right toward the supermarket, and cannot help but jump at a sudden sound.

## Interference and Control

Of course, such complete lapses of inhibition are rare. However, laboratory studies using sensorimotor interference tasks demonstrate that the presence of tempting alternatives affects even successful goal-directed behavior (e.g., Cohen, 2017). In these tasks, participants make speeded responses to designated target stimuli while trying to ignore task-irrelevant distractors. On any given trial, distractors might be associated with the same response as the target (goal-corresponding), with a different response (goal-noncorresponding), or with no response at all (goal-neutral). If participants were truly able to ignore task-irrelevant information, then the target-distractor relationship should make no difference to their behavior. Instead, however, we find that relative to neutral trials, responses are typically faster and more accurate with goal-corresponding distractors, and slower and less accurate with non-corresponding ones. Such interference effects occur across widely different distractor domains, both with target-like distractors presented in close spatial and/or temporal proximity to the target (Eriksen flanker and priming paradigms, respectively; e.g., Eriksen & Eriksen, 1974; Schlaghecken & Martini, 2012), as well as with distractors that are non-target-like stimuli or features, such as the target’s semantic content (Stroop task; Stroop, 1935) or its spatial location relative to the response hand (Simon task; Simon & Rudell, 1967), or unrelated stimuli presented near the response hand (accessory Simon task; Simon & Small, 1969). Behavioral, electrophysiological and hemodynamic measures indicate that across all these domains, distractors tend to automatically trigger at least a partial activation of their associated motor processes (e.g., McBride, Boy, Husain, & Sumner, 2012; Treccani, Cona, Milanesi, & Umiltà, 2018). Should this automatic activation happen to coincide with the response required by the target, performance will

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benefit, but should it happen to coincide with a different response, performance will be impaired.

Logically, the quicker and more effectively such task-irrelevant activations can be overcome, the smaller will be the resulting interference effects. The magnitude of interference effects is therefore often taken as an index of “inhibitory efficiency,” with small interference effects indicating efficient, and large effects indicating inefficient, inhibitory control.<sup>1</sup> Correspondingly, one would expect that persons with poor inhibitory control—for example, young children or individuals diagnosed with attention deficit hyperactivity disorder—show enlarged interference effects, and this is indeed the pattern usually observed (e.g., Mullane, Corkum, Klein, & McLaughlin, 2009).<sup>2</sup>

Interestingly, interference magnitude not only varies between individuals, but also varies systematically with task context: Typically, interference effects are reduced (suggesting more efficient inhibition) (a) when a second goal-noncorresponding distractor is present within the same trial; (b) when a goal-noncorresponding distractor was present on the immediately preceding trial (*Gratton or congruency sequence effect [CSE]; Gratton, Coles, & Donchin, 1992*); (c) in tasks containing mostly noncorresponding distractors; (d) for items mostly paired with noncorresponding distractors; and (e) when an item is presented in a context associated with non-corresponding distractors (*list-wide, item-specific, and context-specific proportion congruency effects* for c–e, respectively; see Bugg & Crump, 2012).

### Domain-Specific Versus Domain-General: A Paradox in Interference Control

At first glance, these results appear to form a compellingly simple and coherent pattern: Inhibitory efficiency increases whenever inhibitory demands are particularly high (due to currently, recently, or typically appearing noncorresponding distractors), and decreases—or “relaxes”—in less demanding situations. However, closer inspection reveals that interpreting this pattern is far from a straightforward task, and the mechanisms that control these (seemingly adaptive) adjustments are still incompletely understood (for reviews, see Braem, Abrahamse, Duthoo, & Notebaert, 2014; Bugg & Crump, 2012; Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a, 2014b; Egner, 2017). Even fundamental questions have not yet been resolved, such as whether inhibitory control (i.e., control of inhibitory processes) really is a strategic top-down “decision” or rather an associative bottom-up “consequence” (e.g., Egner, 2017), whether it is a unitary function or a set of independent, domain-specific processes (e.g., Cohen, 2017), and whether it is a specific response to “conflict” (noncorrespondence) or a general adaptation to any context (e.g., Schlaghecken & Martini, 2012).

A central issue in this research is the *domain-generality* versus *domain-specificity* of CSEs (see Braem et al., 2014; Duthoo et al., 2014a, 2014b; Egner, 2008, 2017): If inhibitory control is a unitary central function that biases processing toward goal-relevant and away from goal-irrelevant information to minimize interference from anticipated conflict, then the specific type of distractor that causes this conflict should not matter. That is, CSEs should be domain-general, such that following a goal-noncorresponding distractor of Type A, interference effects on the next trial should be reduced for Type A distractors as well as for Type B distractors.

Conversely, if CSEs reflect local adjustments within individual sensorimotor pathways, they should be domain-specific (i.e., they should be specific to the preceding trial’s distractor type, such that following a goal-noncorresponding distractor of Type A, interference effects on the next trial should be reduced for Type A distractors, but not for Type B distractors). Although there are exceptions (e.g., Kan et al., 2013), most evidence to date indicates that CSEs are indeed domain-specific. This has been shown for various combinations of distractor domains: A prime’s goal-correspondence on trial  $n$  affects priming but not Simon effects on trial  $n + 1$ , and vice versa (e.g., Egner, Delano, & Hirsch, 2007; Funes, Lupiáñez, & Humphreys, 2010; Schlaghecken, Refaat, & Maylor, 2011<sup>3</sup>), a flanker’s goal-correspondence on trial  $n$  affects flanker but not Simon effects on trial  $n + 1$ , and vice versa (Akçay & Hazeltine, 2011; Wendt, Kluwe, & Peters, 2006), and a cue’s validity on trial  $n$  affects cueing but not Stroop effects on trial  $n + 1$ , and vice versa (Kim, Chung, & Kim, 2012), to name but a few examples.

Such domain-specificity of CSEs has been observed in paradigms in which different interference tasks are mixed (e.g., switching between Simon and Stroop trials, Forster & Cho, 2014, or between Simon and spatial Stroop trials, Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005) as well as in “hybrid” interference paradigms, in which two distractor types are factorially combined on each trial. (E.g., in a prime-Simon hybrid task, each trial contains a prime stimulus followed by a laterally displaced target; both the prime and the target’s location are response-irrelevant distractors that are combined factorially; i.e., prime and location congruency vary independently of each other; see SRM11.) In switching paradigms, the finding of domain-specific CSEs (i.e., the presence of CSEs only on task-repeat trials, not on task-switch trials) might be explained by switching costs, which obviously occur on switch trials only (see Egner, 2008). In hybrid paradigms, no such confound exists. Consequently, the domain-specificity of CSEs in these paradigms provides the strongest evidence yet that rather than involving a general-purpose “inhibitory control center,” distractor-related activation and inhibition

<sup>1</sup> This relationship is not, however, entirely straightforward, as the strength of the automatic motor activation also needs to be taken into account. If distractors fail to trigger their corresponding motor response, then of course no inhibition is needed to prevent interference. For example, in priming tasks, targets are preceded by to-be-ignored distractors (“primes”) that are associated with the same response as the target (goal-corresponding) or with a different response (goal-noncorresponding). Usually, goal-corresponding primes facilitate and noncorresponding primes hinder performance, but these priming effects disappear when primes are perceptually degraded—presumably because degraded primes are too weak to trigger an automatic motor activation, not because their activations are inhibited more strongly (Schlaghecken & Eimer, 2002). Another example is the standard color-word Stroop task, which produces performance costs when the meaning of a color word interferes with the task of naming that word’s print color: Obviously, such interference will only occur in observers able to read the language.

<sup>2</sup> Note, however, that this does not imply a fixed one-to-one relationship between inhibitory control and interference effect magnitude: There is no reason to assume that “inhibitory control” is a single, unitary process, nor that interference effects are driven solely by inhibitory processes.

<sup>3</sup> Henceforth SRM11.

processes are mediated by separate, task- and stimulus-specific sensorimotor pathways.<sup>4</sup>

Paradoxically, hybrid interference paradigms not only provide the strongest support for the domain-specificity of inhibitory control, but also the most direct challenge. Logically, if distractors from different domains are processed within separate sensorimotor pathways, they should produce additive, not interactive, interference effects *within* a given trial. Although such additivity has indeed been observed in several studies (see Table 1 and Rey-Mermet & Gade, 2016, for a brief overview), it is far from being the norm. Across numerous studies and different distractor-type combinations, effects have been found to be underadditive. That is, interference from one distractor is often larger (suggesting reduced inhibition) when the other distractor is congruent, and smaller (suggesting increased inhibition) when it is incongruent (see Table 2 for a list of sensorimotor interference studies in which this pattern has been observed). In other words, whereas a lack of *between*-trial interactions in hybrid tasks suggests that inhibitory control operates strictly locally within each specific sensorimotor pathway, the *within*-trial interactions in the same tasks suggest instead that inhibitory control settings generalize across different distractor domains, either due to a superordinate, domain-general inhibitory control process (e.g., Boy, Husain, & Sumner, 2010; Feldman & Freitas, 2019; Frühholz, Godde, Finke, & Herrmann, 2011; Rey-Mermet & Gade, 2016) or to “cross-talk” between sensorimotor channels (e.g., Stoffels & van der Molen, 1988).

These seemingly contradictory results present a problem for any theory of inhibitory cognitive control, and consequently for developmental and clinical research into inhibitory deficits. If there is a general inhibitory control system that can affect distractor-triggered activity from different domains, as indicated by the within-trial interaction, then why are CSEs typically domain-specific? Conversely, if distractor activation and inhibition is mediated by distractor-domain-specific, independent processes (as suggested by the domain-specificity of CSEs), then how do different distractors interact within a trial?

### Reactivation Aversion Effect: Beyond Domain-Specific Sensorimotor Processes?

A potential solution to this conundrum was proposed by SRM11. Using a hybrid prime-Simon interference task (i.e., targets preceded by task-irrelevant primes and presented at task-irrelevant locations) with additional neutral primes and neutral target locations, SRM11 (a) replicated the seemingly paradoxical pattern of a within-trial interaction with between-trial domain specificity, and (b) established that the former was driven by a selective response slowing on trials with a goal-corresponding prime and a goal-noncorresponding target location. (For convenience, we will refer to a prime’s goal-correspondence as its “compatibility” [compatible or incompatible], and to a target-location’s goal-correspondence as its “congruency” [congruent or incongruent]—hence, selective slowing was observed on compatible-incongruent trials.) These trials are uniquely characterized by a sequence of alternating activations in which a just-discarded response has to be reactivated (e.g., a prime-triggered *right*-hand activation, discarded in favor of a location-triggered *left*-hand activation, then reactivated to execute a *right*-hand target response;<sup>5</sup> see Figure 1, bottom left). Having to reactivate a

just-discarded response typically results in behavioral costs, as evidenced by numerous negative aftereffects like negative compatibility effects (NCEs) with subliminal (e.g., Eimer & Schlaghecken, 1998) or supraliminal (e.g., Machado, Wyatt, Devine, & Knight, 2007) primes, inhibition of return (IOR; Taylor & Klein, 2000), negative priming (NP; Frings, Schneider, & Fox, 2015), and N-2 repetition costs (Mayr & Keele, 2000). The most parsimonious explanation of the specificity/interaction paradox thus seems to be that responses on prime-compatible location-incongruent trials similarly suffer from reactivation costs (termed by SRM11 a “reactivation aversion effect” [RAE]).

Potentially, the RAE contains the solution to the specificity/interaction paradox because, rather than reflecting interacting sensorimotor processes, it might be due to processing difficulties or confusion at a higher-level monitoring or decision stage (“*go right . . . no, go left . . . hold on, go right after all . . .*”). In support of the “high-level confusion” account, SRM11 observed RAEs with clearly visible (nonmasked) primes, but not with masked, subjectively invisible primes. However, this evidence is not conclusive. At the relatively long (150 ms) prime-target interstimulus interval (ISI) employed in that study, motor processes with masked and nonmasked primes are not equivalent: Whereas nonmasked prime-Simon trials elicit a sequence of three motor responses (prime-activated, location-activated, target identity-activated), masked prime-Simon trials elicit a series of four, as an additional inhibition process reverses the initial prime activation (Eimer & Schlaghecken, 1998), thus potentially obscuring any RAEs. Because of its potential relevance to the cognitive control literature, the present study therefore aimed to obtain more conclusive evidence about the nature of the RAE, in particular, whether it originates at the level of sensorimotor interference, and thus poses a conceptual problem for theories based on domain-specificity of sensorimotor processes, or whether it originates at subsequent, higher-level monitoring and decision stages, thereby resolving the apparent specificity/interaction paradox.

### Alternative Accounts

First, however, it needs to be demonstrated that this paradox—within-trial interactions in the presence of domain-specific, but not domain-general, CSEs—is a genuine phenomenon, not an artifact resulting from experimental confounds. The issue of such confounds is hotly debated in the CSE literature. On the one hand, CSEs are often assumed to reflect cognitive control in the sense of strategic top-down adjustment of attention toward task-relevant (target) and away from task-irrelevant (distractor) information (e.g., Duthoo et al., 2014a, 2014b; Gratton et al., 1992; Verguts & Notebaert, 2008, 2009). However, various accounts have challenged this interpretation, attributing CSEs to bottom-up associative processes instead.

<sup>4</sup> This notion is further supported by the lack of reliable correlations between interference effects from different sensorimotor tasks (Hedge, Powell, & Sumner, 2018b) and the fact that they appear to involve different, if overlapping, cortical areas (e.g., Fan, Flombaum, McCandliss, Thomas, & Posner, 2003).

<sup>5</sup> Although target location and target identity are, of course, presented simultaneously, the former affects the motor system before the latter does (Cespón et al., 2013; Finkbeiner & Heathcote, 2016).

Table 1

*Studies Reporting Additive Within-Trial Interactions Between Distractor Domains for Response Times in Hybrid Interference Tasks*

Interference domains	Study	Study details	
		(a) CSE?	(b) Confound-controlled?
Simon × Duration	Kunde & Stöcker, 2002	0	no
Simon × Emotional Valence	Kunde, Augst, & Kleinsorge, 2012	S	no
Simon × Stroop*	Simon & Berbaum, 1990	—	—
	Kornblum, 1994	—	—
	Hommel, 1997 (Exp. 1)	—	—
	Egner, Delano, & Hirsch, 2007	S	no
	Chmielewski & Beste, 2019	—	—
Spatial Stroop × Simon*	Li, Nan, Wang, & Liu, 2014	—	—
Simon × Color Flanker	Akçay & Hazeltine, 2011	G	partially
	Scerrati, Lugli, Nicoletti, & Umiltà, 2017	—	—
Spatial Stroop × Flanker	Peschke et al., 2016	—	—
	Korsch, Frühholz, & Herrmann, 2016	—	—
Masked Prime × Flanker*	Bensmann, Vahid, Beste, & Stock, 2019	—	—
Masked Prime × Simon	Schlaghecken, Refaat, & Maylor, 2011 (SRM11)	0	no
Word Stroop × Color Stroop	Henik, Ro, Merrill, Rafal, & Safadi, 1999	—	—

*Note.* Studies are grouped according to the interference domains under investigation. The table additionally lists for each study (a) whether congruency sequence effects (CSEs) were investigated (“—” = not investigated), and if so, whether they were found not to be present at all (0), domain-specific (S), or domain-general (G); and (b) if CSEs were investigated, whether there was a control of possible confounds.

\* See Table 2 for similar paradigms with reactivation aversion-like effects.

According to the repetition priming account (e.g., Mayr, Awh, & Laury, 2003) and the feature integration account (e.g., Hommel, Proctor, & Vu, 2004), CSEs merely reflect response time (RT) differences between trials that are identical repetitions of the previous trial and trials that are not. Partly in response to this challenge, various studies have increased the number of stimulus-response (S-R) pairings in order to be able to implement trial-type repetitions without feature repetitions. However, because each target can only have one goal-corresponding feature, but multiple goal-noncorresponding ones, this produces a problem with balancing correspondence conditions and stimulus features. Contingency learning accounts of CSEs (e.g., Mordkoff, 2012) point out that (a) participants can learn that distractors are informative with regard to the required response and thus respond more quickly on goal-corresponding trials; and that (b) this effect is cumulative, that is, responses to corresponding/highly contingent trials are even faster when the previous trial was also corresponding/highly contingent, resulting in larger interference effects following corresponding/highly contingent trials than following noncorresponding/noncontingent trials. Consequently, in studies with more than two S-R mappings, CSEs might really be “contingency sequence effects”—again only mimicking cognitive control of sensorimotor processes.

### The Present Study

If, as these alternative accounts suggest, CSEs are not “real”—that is, if they result from experimental confounds rather than reflecting cognitive control processes—then the apparent conflict between domain-specific between-trial and domain-general within-trial effects could similarly be regarded as a quirk driven by specific experimental conditions rather than a fundamental paradox in cognitive control research. Therefore, the initial step of the present study (Experiment 1) was to demonstrate that within-trial interactions in a hybrid sensorimotor interference task do indeed occur together with domain-specific CSEs in a paradigm that is

free of any confounds. This can be achieved by splitting an interference task with four S-R assignments (e.g., left-, right-, up-, and down-pointing arrows, requiring corresponding left, right, up, and down responses) into two separate, nonoverlapping tasks (e.g., left/right vs. up/down). Tasks alternate across trials (thus avoiding immediate repetitions), and within each, there are as many corresponding as noncorresponding stimulus combinations (thus preventing contingency learning). Previously, the same logic has been applied to study CSEs for a single distractor domain (e.g., Mayr et al., 2003; Weissman, Jiang, & Egner, 2014; see Egner, 2008, 2017, for reviews). To the best of our knowledge, however, the present study is the first to use this design in a hybrid interference task with two independent and fully factorially combined distractor types. The results will therefore not only be of interest to the study of the RAE, but will also provide a new type of evidence regarding the domain-specificity versus domain-generality of CSEs.

Using the same hybrid prime-Simon task—though only in the two-alternative version—Experiments 2 and 3 then investigated whether the RAE is best understood in terms of inhibitory interactions affecting low-level sensorimotor processes, or as reflecting “confusion” at higher-level action- or decision-monitoring stages. To this purpose, Experiment 2 examined whether stimuli of which participants are not consciously aware would still give rise to RAEs: If they do, then the RAE would need to be explained in terms of low-level sensorimotor processes, but if they do not, this would provide evidence in favor of a more high-level account. Finally, Experiment 3 investigated whether RAEs in older adults are smaller or larger than those in young adults: Again, the former would be consistent with a sensorimotor inhibition interpretation of RAEs, the latter with a high-level account.

### Experiment 1: Four Response Alternatives

Experiment 1 aimed to (a) replicate SRM11’s central finding of a within-trial interaction of prime compatibility and target-location

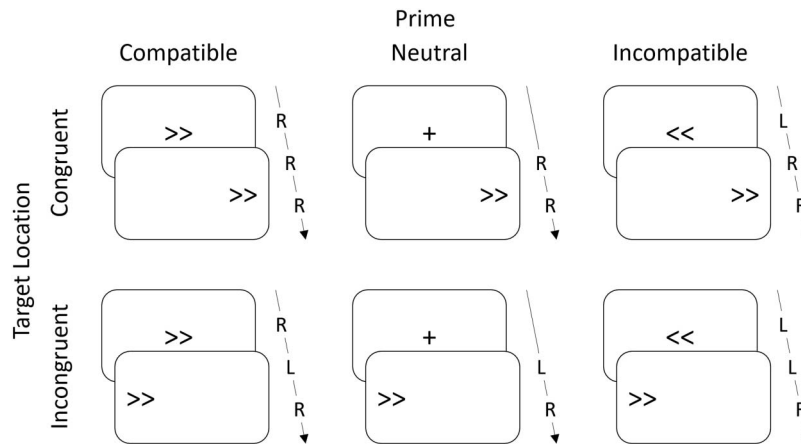
**Table 2**  
*Studies Reporting Under-Additive Within-Trial Interactions Between Distractor Domains for Response Times in Hybrid Interference Tasks*

Interference domains	Study	Study details			
		(a) Stimuli	(b) Neutral baseline	(c) CSE? <sup>a</sup>	(d) Confound-controlled?
Flanker × Simon	Hommel, 1997 (Exp. 2)	letters	no	—	—
	Fan, Flombaum, McCandliss, Thomas, & Posner, 2003 (Exp. 4)	arrows	no	—	—
Flanker × Flanker Simon Flanker × Auditory Accessory Simon Flanker × Letter-Stroop	Wendt, Klauwe, & Peters, 2006 (Exp. 2A)	letters <sup>a</sup>	no	S	no
	Frihholz, Godde, Finke, & Herrmann, 2011 <sup>b</sup>	colored dots	no	—	—
	Rey-Mermet & Gade, 2016 (Exp. 3)	colored X-strings	no	S	no
	Treccani, Cubelli, Della Sala, & Umiltà, 2009	colored squares	Flanker	—	—
	Stoffels & van der Molen, 1988 (Exp. 2)	arrows <sup>c</sup>	both	—	—
	Rey-Mermet & Gade, 2016 (Exp. 1)	colored words/letters	no (1a,b) both (1c)	0	post-hoc
	Rey-Mermet, Gade, & Steinhauser, 2019	colored words/letters	no	0 <sup>d</sup>	post-hoc
	Boy, Hussain, & Sumner, 2010 (Negative Compatibility Effect condition <sup>e</sup> )	arrows	Flanker (suppl. Exp. 2)	S <sup>f</sup>	no
	Bensmann, Roessner, Stock, & Beste, 2018 <sup>g</sup>	arrows	no	—	—
	Kunde & Wühr, 2006 (Exp. 2 <sup>h</sup> )	arrows	no	G <sup>i</sup>	no
Prime × Simon	Schlaghecken et al., 2011 (SRM11)	arrows	Simon (Exp. 1) Prime (Exp. 2)	S	no
	Mückschel, Stock, Dippel, Chmielewski, & Beste, 2016 <sup>b,j</sup>	colored words/letters	no	S(Part) <sup>k</sup>	post-hoc
	Rey-Mermet & Gade, 2016 (Exp. 2)	words	Stroop	—	—
	De Jong, Liang, & Lauber, 1994 (Exp. 3)	triangles	no	I	post-hoc
	Feldman & Freitas, 2019	letters	no	—	—
	Hommel, 1997 (Exp. 3)	colored lights & response keys	no	—	—
	Hedge & Marsh, 1975	color patches	no	—	—
	De Jong et al., 1994 (Exp. 1, Exp. 4 <sup>b</sup> )	color patches	no	—	—
	Ivanoff, Klein, & Lupiáñez, 2002	Various <sup>m</sup>	n/a	n/a	n/a
	Wang, Fuentes, Vivas, & Chen, 2013 <sup>b</sup>	colored squares	no	—	—
IOR <sup>l</sup> × Simon	Vivas & Fuentes, 2001	colored squares	Stroop	—	—
	Chen, Wei, & Zhou, 2006	color words	Stroop	—	—
IOR × Stroop	Fuentes, Vivas, & Humphreys, 1999 (Exp. 1, Exp. 2)	color words (Chinese)	no	—	—
	Fuentes et al., 1999 (Exp. 3, Exp. 4)	words	no	—	—
IOR × Semantic Priming IOR × Flanker	Vivas, Fuentes, Estévez, & Humphreys, 2007	letters, digits	no	—	—
		colored shapes	Shape, Color	—	—

*Note.* S-R = stimulus response. Studies are grouped according to the interference domains under investigation. The table additionally lists for each study (a) the type of stimuli used to instantiate the interference domains; (b) whether or not a neutral baseline condition was included, and if so, for which domain; (c) whether congruency sequence effects (CSEs) were investigated (“—” = not investigated, and if so, whether they were found not to be present at all (0), present but generality/specificity not investigated/reported (1), domain-specific (S), or domain-general (G); and (d) if CSEs were investigated, whether there was a control of possible confounds, and if so, how this was done.

<sup>a</sup> The corresponding experiment with color-word Stroop stimuli did not produce a within-trial interaction. <sup>b</sup> Also report electrophysiological and/or hemodynamic measures for each interference condition (studies that report electrophysiological/hemodynamic measures, but do not do so separately for each interference condition, are not marked here). <sup>c</sup> The corresponding experiment with letters instead of arrows (Exp. 1) did not produce a within-trial interaction. <sup>d</sup> According to 24part\_all\_rt\_no\_stat.txt, available at <https://osf.io/2v857/>. <sup>e</sup> The corresponding positive compatibility effect condition (i.e., short prime-target ISI) did not produce a within-trial interaction. <sup>f</sup> Experiment 3 and Supplemental Experiment 3: Previous flanker congruency interacted with NCE; effect of previous prime compatibility not investigated. <sup>g</sup> Other studies from this lab, using the same paradigm, did not obtain within-trial interactions (Bensmann, Zink, Arning, Beste, & Stock, 2019; Stock, Friedrich, & Beste, 2016). <sup>h</sup> The corresponding experiment with letters instead of arrows (Exp. 1) did not produce a within-trial interaction. <sup>i</sup> Primes, like the targets, were presented laterally displaced, hence domains were mixed rather than clearly separate in this study. <sup>j</sup> Nonsignificant trend (significant in one-tailed test); note that the authors refer to the prime as a “flanker-like cue.” <sup>k</sup> “Part” = partial: Previous Stroop congruency affected Stroop effects, but previous location congruency did not affect Simon effects. <sup>l</sup> IOR = inhibition of return. <sup>m</sup> Review and reanalysis of 13 published experiments.

<sup>n</sup> See Table 1 for similar paradigms without reactivation aversion-like effects.



*Figure 1.* Hybrid prime-Simon task with neutral primes: Participants respond to the pointing direction of the target arrow with a spatially corresponding key press, while trying to ignore the preceding prime (compatible, neutral, or incompatible with respect to the required response) and the target's location (congruent or incongruent with the response hand). Letters along the arrows indicate the sequence of response activations triggered by first the prime, then the target location, and lastly the target identity (R = right hand, L = left hand).

congruency driven by a selective slowing on compatible incongruent trials (RAE) in the absence of domain-general (but presence of domain-specific) CSEs in (b) a paradigm in which CSEs can unequivocally be interpreted as reflecting sensorimotor adaptations to the goal-correspondence or goal-noncorrespondence of the preceding trial's distractor. To achieve this, we combined the left-right prime-Simon task of the original study with a conceptually identical up-down prime-Simon task such that stimulus and response directions (horizontal vs. vertical) alternated trial-to-trial. As noted above, such a design not only prevents stimulus and response repetitions, but also avoids any contingencies between stimuli and goal-correspondence conditions. Furthermore, because targets are directional arrows that require a spatially corresponding response, working memory load does not increase from the two- to the four-alternative choice version of the paradigm (i.e., there is still only one thing to remember: “respond to the direction of the target arrow”).

## Method

**Participants.** The original SRM11 study had a sample size of 20 young participants. Following Simonsohn's (2015) advice for investigating null effects in a replication, we aimed for a sample size 2.5 times as large as the original, namely, 50 participants. To achieve this number, we tested 73 volunteers. Data from two participants were lost due to a recording error, and a further 21 participants were excluded due to insufficient numbers of valid trials in at least one of the cells (see below). According to self-report, the remaining 50 participants were 18–22 years old ( $M = 18.5$ ;  $SD = 0.9$ ), three were male and 47 were female, six were left-handed and 44 were right-handed, and all had normal or corrected-to-normal vision. All were first-year psychology students at the University of Warwick who volunteered to take part for course credit.<sup>6</sup>

**Stimuli.** Primes were directional (up, down, left, or right) double arrows or single plus signs, and targets were directional double arrows (see Figures 1 and 2). All stimuli were presented in

black on a white background and subtended a visual angle of  $0.9^\circ \times 0.9^\circ$ . Primes always appeared at the center of the screen. Targets appeared  $6^\circ$  to the left or right of the center or  $4^\circ$  above or below the center (in line with the steeper decline of contrast sensitivity along the vertical than the horizontal axis [e.g., Rijdsdijk, Kroon, & van der Wildt, 1980], and with pilot testing indicating that these distances produced similar RTs for horizontal and vertical targets).

**Procedure.** Testing took place in individual sessions. Participants were seated in a dimly lit, sound-attenuated cubicle approximately 100 cm in front of a CRT monitor. Each trial began with the presentation of a prime for 33 ms in the center of the screen, followed 150 ms later by a target presented for 100 ms in one of the four possible target locations. The intertrial interval (ITI) was 1,317 ms. The experiment consisted of alternating horizontal trials and vertical trials (see Figure 2). On horizontal trials, all stimulus dimensions were horizontally aligned: Primes were either left- or right-pointing arrows or a plus sign, target arrows appeared on the left or right of fixation and pointed either to the left or to the right, and participants had to give a corresponding left or right response. On vertical trials, all stimulus and response dimensions were vertically aligned: Primes were either up- or down-pointing arrows or a plus sign, target arrows appeared above or below fixation and pointed either up or down, and participants had to give a corresponding up or down response.

<sup>6</sup> All experiments reported in this article were approved by the University of Warwick's Humanities and Social Sciences Research Ethics Committee. Before signing up, and again upon arrival at the lab, participants were warned that the experiment contained rapidly flashing high-contrast stimuli and were explicitly told not to take part if they were photosensitive. Participants were then given a demonstration of the procedure before providing written informed consent. Across all experiments reported here, no participant initially reported to be photosensitive; after seeing the demonstration, one participant stated that the flashing stimuli felt uncomfortable and consequently aborted the experiment. For all participants taking part for course credit, alternative means to gain credits were available.

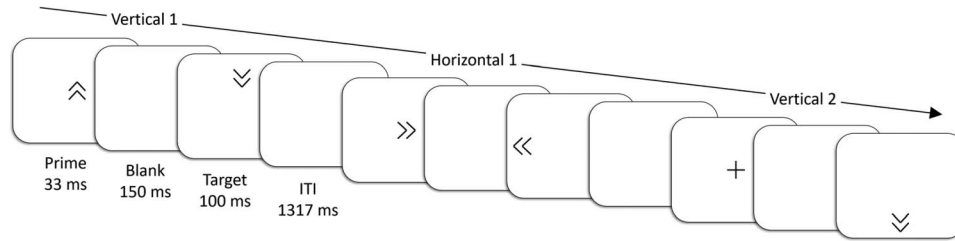


Figure 2. Trial structure and example trial sequence in Experiment 1. ITI = intertrial interval.

On prime-compatible trials, prime and target arrows pointed in the same direction, on prime-incompatible trials, they pointed in opposite directions, and on prime-neutral trials, the prime was a plus sign. On location-congruent trials, the location and the pointing direction of the target arrow matched (e.g., a down-pointing arrow appearing below fixation), whereas on location-incongruent trials, they were in opposition (e.g., a down-pointing arrow appearing above fixation). Within each orientation (horizontal, vertical), all trial types (three prime compatibilities, two location congruencies, two target identities) were equiprobable and completely randomized. Horizontal and vertical trials strictly alternated, so that no primes (except neutral ones), locations, targets, or responses could repeat from one trial to the next (see Figure 2). Order of trial types was pseudorandomized to ensure that all types of transitions (e.g., horizontal compatible congruent followed by vertical compatible congruent, vertical compatible congruent followed by horizontal incompatible incongruent, etc.) were approximately equiprobable. Excluding the first trial of each block, each transition type appeared on average 15.9 times (lowest average: 14.7, highest average: 16.9).

Participants were instructed to ignore the prime and the target location, and to respond to the direction of the target arrow as quickly and accurately as possible by making a corresponding key-press with their right index or middle finger (whichever they preferred) on the number key pad of a standard QWERTY keyboard. The center key (5) was the designated “home” key, and responses were made by moving the finger from the home key to the key that corresponded to the arrow direction (i.e., to the 8 [above the center] for an up-ward pointing arrow, to the 2 [below] for a down-ward pointing one, and correspondingly to the 4 [left] or to the 6 [right] for left- or right-pointing target arrows). After pressing the response key, they were to return immediately to the home key in preparation for the next response (key-presses on the home key were neither required nor recorded).

In order to familiarize participants with task requirements, two practice blocks were administered. In the first (16 trials), stimulus presentation was slowed to half of the normal speed; in the second (32 trials), stimulus presentation was the same as in the experiment. If participants produced more than 25% errors in the second practice block, were exceedingly slow (average RTs >1,000 ms), or otherwise indicated that they struggled with the task, the practice block was repeated. During practice, the experimenter remained in the cubicle to ensure that participants understood and complied with task instructions.

Following practice, the experiment consisted of eight experimental blocks, each containing 144 trials. Participants started the next block when they felt ready to do so. They were encouraged to

leave the cubicle for a break after the fourth block, during which they were offered tea/coffee and biscuits. Including instruction, practice, breaks, and debriefing, the experiment took approximately 50 min.

**Data analyses.** Data were sorted according to orientation (horizontal, vertical), prime compatibility (compatible, neutral, incompatible), location congruency (congruent, incongruent), previous trial’s prime compatibility, and previous trial’s location congruency, resulting in 72 trial types. For RT analyses, only correct-response trials following a correct response were taken into account (93.9% of all correct responses). Participants who had fewer than five valid trials in any condition were excluded from analysis; no further data trimming procedures were employed. For error rate analyses, only errors following a correct response were taken into account (89.9% of all errors). Mean RTs were analyzed using a 2 (orientation)  $\times$  3 (prime compatibility)  $\times$  2 (location congruency)  $\times$  3 (previous prime compatibility)  $\times$  2 (previous location congruency) within-subject ANOVA. For the sake of brevity, we only report within-trial error rate analyses here, based on a 2 (orientation)  $\times$  3 (prime compatibility)  $\times$  2 (location congruency) within-subject ANOVA. Greenhouse-Geisser corrections were applied where appropriate. For a full analysis of sequential (as well as response-latency based) error rate effects, the reader is referred to the [online supplemental materials](#).

For follow-up analyses, priming effects were calculated as prime benefits (neutral minus compatible) and prime costs (incompatible minus neutral), separately for each orientation (two), location congruency (two), and—for RTs only—previous trial type (six), resulting in 24 RT benefits and 24 RT costs, and in four error-rate benefits and four error-rate costs. Correspondingly, Simon effects were calculated as incongruent minus congruent, separately for each orientation (two), prime compatibility (three), and—for RTs only—previous trial type (six), resulting in 36 RT Simon effects and six error-rate Simon effects. RAEs were calculated as Simon effects on prime-compatible trials minus Simon effects on prime-neutral trials, separately for each orientation and—for RTs only—previous trial type, producing 12 RT RAE and two error-rate RAE values. Repeated-measures ANOVAs and *t* tests were used to analyze these effects (for 95% confidence intervals for effects in all three experiments, see the [online supplemental materials](#)).

## Results

Participants produced an average of 14.2 valid correct responses and an average of 0.7 valid errors per condition.

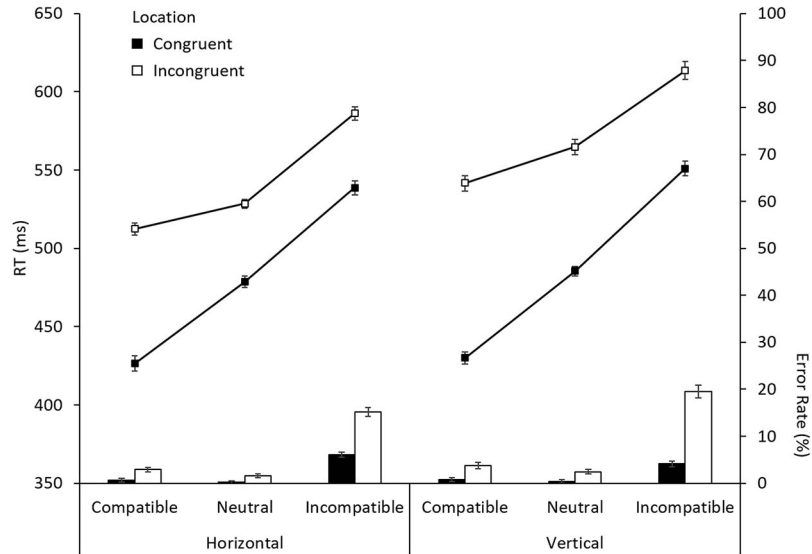


Figure 3. Response times (RTs; lines) in milliseconds (ms) and percentage error rates (bars) in Experiment 1 as a function of prime compatibility, plotted separately for horizontal and vertical trials, and for congruent (black) and incongruent (white) target locations. Error bars represent  $\pm 1$  SEM after removal of between-subjects variability (see Cousineau, 2005).

**Within-trial effects (see Figure 3).** Error rates were higher on vertical than on horizontal trials,  $F(1, 49) = 4.99, p = .030, MSE = 16.63, \eta_p^2 = .092$ , especially for location-incongruent trials,  $F(1, 49) = 16.62, p < .001, MSE = 14.97, \eta_p^2 = .253$ . They showed significant priming and Simon effects, both  $F_s > 43$ , both  $p_s < .001$ , both  $\eta_p^2$  s  $> .68$ , which interacted in a superadditive way,  $F(1.22, 59.85) = 72.68, p < .001, MSE = 38.42, \eta_p^2 = .597$ , as error rates were particularly high on prime-incompatible location-incongruent trials—especially in the vertical orientation condition,  $F(1.35, 67.33) = 17.66, p < .001, MSE = 10.58, \eta_p^2 = .265$ —whereas with compatible and

neutral primes, participants produced very few errors on either congruent or incongruent trials.

Full ANOVA results of the RT analysis are listed in Table 3, and correspondingly indicated below in square brackets. As can be seen from Figure 3, RTs were longer on vertical than on horizontal trials [Table 3, 1a], specifically when trials were location incongruent [3b]. Both the priming effect (longest RTs on prime-incompatible and shortest on prime-compatible trials) and the Simon effect (longer RTs on location-incongruent than on location-congruent trials) were significant [2a][3a]. Prime compatibility and target location congruency interacted in the

Table 3  
Full ANOVA Results for Response Times in Experiment 1

Factors	(a) Effects					(b) $\times$ Orientation				
	df	F	p	MSE	$\eta_p^2$	df	F	p	MSE	$\eta_p^2$
1. Orientation	1, 49	31.22	<.001	10699.64	.389	—	—	—	—	—
2. Prime	1.27, 62.27	222.99	<.001	18922.84	.820	1.55, 75.69	0.92	.380	2369.94	.018
3. Location	1, 49	227.82	<.001	20773.63	.823	1, 49	53.21	<.001	2341.68	.521
4. Prime $\times$ Location	2, 98	74.13	<.001	2088.21	.602	2, 98	4.09	.020	968.79	.077
5. Prev. Prime	1.63, 79.90	55.90	<.001	2021.17	.533	1.90, 92.93	2.17	.123	712.26	.042
6. Prev. Location	1, 49	94.28	<.001	866.78	.658	1, 49	7.39	.009	876.81	.131
7. Prev. Prime $\times$ Prev. Location	2, 98	1.57	.214	754.96	.031	2, 98	3.42	.037	684.76	.065
8. Prev. Prime $\times$ Prime	3.47, 169.91	35.40	<.001	969.39	.419	4, 196	0.47	.758	694.45	.009
9. Prev. Location $\times$ Location	1, 49	97.68	<.001	965.13	.666	1, 49	0.19	.665	698.76	.004
10. Prev. Location $\times$ Prime	2, 98	0.63	.537	947.92	.013	2, 98	0.18	.835	1050.01	.004
11. Prev. Prime $\times$ Location	2, 98	1.24	.294	774.11	.025	2, 98	0.40	.669	803.18	.008
12. Prev. Prime $\times$ Prev. Location $\times$ Prime	4, 196	0.60	.662	766.31	.012	3.35, 164.32	0.43	.757	1033.47	.009
13. Prev. Prime $\times$ Prev. Location $\times$ Location	2, 98	0.43	.655	793.05	.009	2, 98	1.83	.166	703.41	.036
14. Prev. Prime $\times$ Prime $\times$ Location	4, 196	2.98	.020	792.29	.057	3.24, 158.80	1.03	.384	1006.39	.021
15. Prev. Location $\times$ Prime $\times$ Location	2, 98	0.48	.618	843.65	.010	2, 98	<.01	.996	756.49	<.001
16. Prev. Prime $\times$ Prev. Location $\times$ Prime $\times$ Location	2.95, 144.35	1.76	.159	1004.95	.035	3.44, 168.40	2.14	.088	791.05	.042

Note. Prev. = previous. Greenhouse-Geisser corrections indicated by non-integer degrees of freedom. Significant p values highlighted in bold.



form of an RAE [4a], which was more pronounced on horizontal than on vertical trials [4b].

To further examine the RAE pattern, we calculated Simon effects for each prime and orientation condition separately (averaged across previous trial conditions). For the horizontal orientation, Simon effects were significantly larger on compatible-prime than on neutral-prime trials (85 and 50 ms, respectively),  $t(49) = 9.60$ ,  $p < .001$ , and indistinguishable from each other on neutral-prime and incompatible-prime trials (48 ms),  $t < 1$ . For the vertical orientation, Simon effects were similarly enlarged on compatible- relative to neutral-prime trials (111 vs. 79 ms),  $t(49) = 6.43$ ,  $p < .001$ , but were reduced on incompatible-prime trials (63 ms) relative to neutral-prime trials,  $t(49) = 3.53$ ,  $p < .001$ .

**Between-trial effects.** Responses were on average 15 ms slower following incompatible primes than following compatible or neutral primes [5a], and 10 ms slower following incongruent than following congruent target locations [6a]. The latter effect was more pronounced on horizontal than on vertical trials [6b], but follow-up tests (two separate ANOVAs, one for each orientation) confirmed that it was significant for both,  $ps < .001$ . The three-way interaction with orientation [7b] was due to the fact that for horizontal trials, previous prime and previous target location interacted (mimicking the RAE pattern),  $F(2, 98) = 3.62$ ,  $p = .031$ ,  $MSE = 882.99$ ,  $\eta_p^2 = .069$ , whereas for vertical trials, this was not the case,  $F < 1$ .

Importantly, results revealed substantial domain-specific CSEs [8a][9a], but no domain-general CSEs [10a][11a]. As can be seen from Figure 4, overall priming effects (benefits plus costs) were enlarged following prime-compatible and reduced following prime-incompatible trials but were unaffected by the preceding trial's location congruency (Panel A).<sup>7</sup> Conversely, Simon effects were larger following trials with congruent than following trials with incongruent target location but were unaffected by the preceding trial's prime compatibility (Panel B). Finally, a three-way interaction between previous prime, current prime, and current target location [14a] reflected the fact that the domain-specific priming CSE (i.e., reduction in overall priming effects from previous compatible to previous neutral to previous incompatible trials) was more pronounced on location-congruent trials (38 ms, priming effects decreasing from 132 to 120 to 94 ms) than on location-incongruent trials (26 ms, priming effects decreasing from 83 to 77 to 57 ms).

To further test the absence of domain-general CSEs, we directly compared interference effects (priming effect = prime-incompatible RT – prime-compatible RT; Simon effect = location-incongruent RT – location-congruent RT) following consistent versus inconsistent cross-domain distractors (i.e., priming effects following location-congruent vs. location-incongruent trials, and Simon effects following prime-compatible vs. prime-incompatible trials) with Bayesian  $t$  tests using JASP (standard Cauchy prior width 0.707). Vertical Simon effects showed only weak evidence for  $H_0$  ( $BF_{01} = 2.83$ ), while horizontal Simon effects and both vertical and horizontal priming effects all showed moderate evidence for  $H_0$  ( $BF_{01} = 3.36$  to 5.31). That is, depending on the exact test parameters and comparisons, priming and Simon effects are estimated to be approximately two to five times more likely to be unaffected by the previous trial's opposite distractor type than to be affected by it.

## Discussion

Experiment 1 produced two main results. First, it successfully replicated the RAE pattern reported in SRM11: Within a given trial, prime compatibility and target location congruency interacted, and whereas for error rates, this interaction was primarily driven by exaggerated error rates on prime-incompatible location-incongruent trials, for RTs, it was primarily—for horizontal trials even exclusively—driven by a slowing of responses to prime-compatible location-incongruent targets. Second, the experiment confirmed the existence of domain-specific and absence of domain-general CSEs in a paradigm free of any repetition or contingency confounds. Consequently, confound models cannot account for the present results, nor can models based on the notion of abstract, general-purpose conflict adaptation (e.g., Duthoo et al., 2014a, 2014b; Gratton et al., 1992; Verguts & Notebaert, 2008, 2009), at least not without making substantial additional assumptions. Instead, this pattern strongly suggests that CSEs do indeed reflect trial-by-trial adaptations to a distractor's goal-correspondence or goal-noncorrespondence (in contrast to confound accounts), and that these adaptations occur through up- and down-regulations within *distractor*-specific sensorimotor pathways rather than reflecting a top-down controlled enhancement of *target*-related processing (in contrast to conflict adaptation accounts).

At first glance, the claim that distractor-related activation and inhibition processes occur within separate sensorimotor pathways seems inconsistent with the finding of within-trial distractor interactions, which might be taken as evidence for domain-general inhibitory control processes (e.g., Boy et al., 2010; Feldman & Freitas, 2019; Frühholz et al., 2011; Rey-Mermet & Gade, 2016) or cross-talk between sensorimotor channels (e.g., Stoffels & van der Molen, 1988). However, the RAE pattern of these interactions—that is, the selective slowing of responses on prime-compatible location-incongruent trials—suggests a different interpretation. As outlined in the Introduction, these trials are uniquely characterized by the need to reactivate a just-discarded response activation (e.g., right prime-induced activation → left location-induced activation → right target-related activation; see Figure 1). Given the number and variety of tasks producing negative after-effects of just-discarded activity, such reactivation seems inherently difficult and behaviorally costly. However, the reasons for these costs are not necessarily clear, and might indeed differ between different tasks or task features (see, e.g., Frings et al., 2015; Kiesel et al., 2010; Schlaghecken & Eimer, 2006; and Taylor & Klein, 2000, for discussions of various mechanisms of NP, N-2 repetition costs, the NCE, and IOR, respectively).

For the RAE, four—not necessarily mutually exclusive—explanations seem intuitively plausible. The first one is trivial: Given the disproportionately enlarged number of errors on incompatible-incongruent trials, might the RT-RAE merely be the result of a speed-accuracy trade-off? This seems unlikely. First, as noted above, the Prime × Simon interaction on error rates is likely to be due to floor effects for compatible and neutral primes. Second, it should be emphasized that the overall

<sup>7</sup> Although the domain-specific CSE was particularly prominent for prime benefits, follow-up analyses confirmed that it was significant for both benefits and costs,  $ps < .001$ .

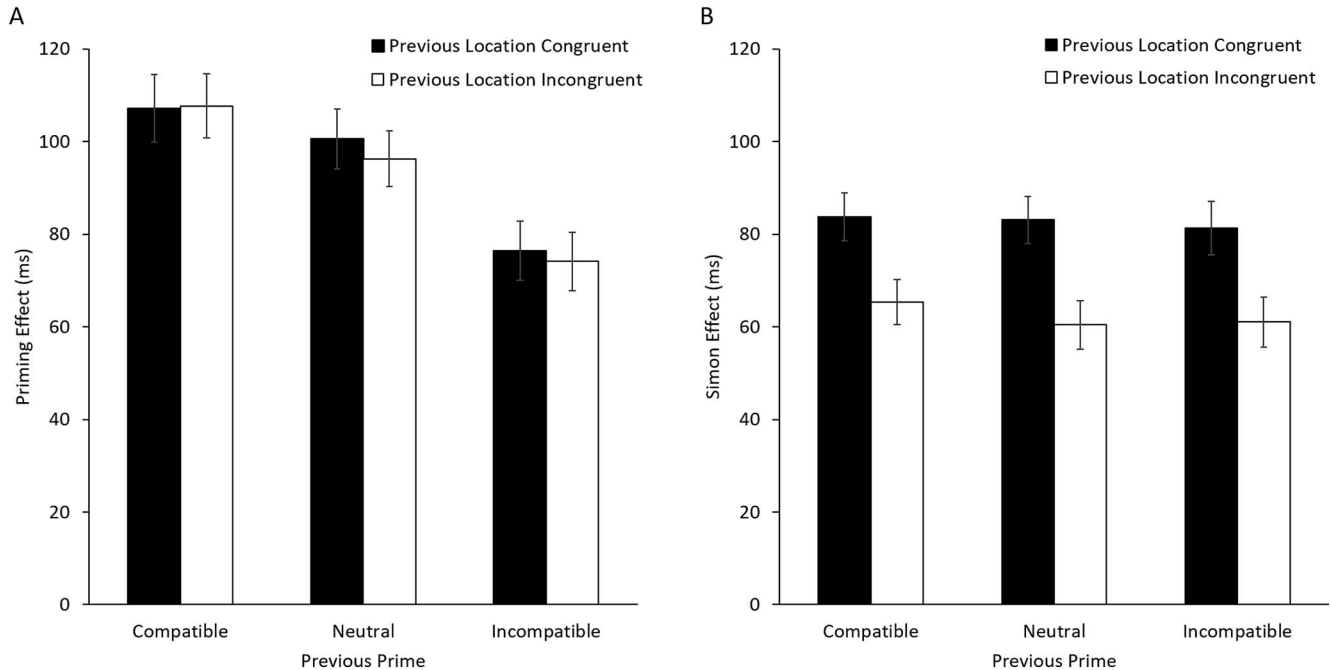


Figure 4. Priming effects (A) and Simon effects (B) as a function of the previous trial's prime compatibility and location congruency. Error bars represent  $\pm 1$  SEM.

data pattern does not indicate a speed–accuracy trade-off, as higher error rates coincide with slower responses and lower error rates with faster ones. In particular, third, the critical prime-compatible location-incongruent condition, assumed to be selectively slowed, shows error rates that are numerically (though not statistically) higher than those in the prime-neutral location-incongruent condition, that is, the opposite of a speed–accuracy trade-off pattern. Finally, it should be noted that the vast majority of errors occur within the fastest 20% of all responses, yet the RAE emerges only at longer latencies and is noticeably absent within the first RT quintile (see [online supplemental materials](#) for details).

The three remaining, theoretically more interesting, explanations for the RAE are motor inhibition, visual attention, and high-level response scheduling confusion. According to the inhibition hypothesis, the initial, prime-triggered motor activation will be inhibited by the opposite-hand location-triggered motor activation, and as a result will take longer to become sufficiently reactivated for response execution. This hypothesis has the advantage of being simple and intuitively plausible. However, because it assumes an interaction between distractor processes, it cannot easily be reconciled with the CSE results. More importantly, the hypothesis predicts not only reduced prime benefits on location-incongruent trials (i.e., the RAE), but also reduced prime costs on location-congruent trials. On these trials, prime- and location-triggered activations are in opposition when primes are incompatible (e.g., left prime  $\rightarrow$  right location  $\rightarrow$  right target). If opposing location activation (“right”) inhibits the initial prime-triggered activity (“left”), then this activity should have a correspondingly reduced impact on overt performance (“right”) than on trials where prime- and location-triggered activity are in accordance (i.e., costs

caused by an incompatible prime should be smaller on location-congruent than on location-incongruent trials). Clearly, this was not the case in the present experiment, nor in the SRM11 study.

The visual attention hypothesis faces a similar issue. This hypothesis is based on the possibility that directional arrow primes might automatically shift the focus of visual attention to the indicated location, and that relative to an “unfocused” condition, target identification will be facilitated for targets appearing inside this focus, and will be delayed for targets appearing on the opposite side (see [online supplemental materials](#) for a schematic illustration). Consequently, Simon effects will be enlarged on compatible relative to neutral trials (i.e., the RAE), because attention-related costs and benefits coincide with location-related costs and benefits. By the same token, however, Simon effects should show a corresponding reduction on incompatible relative to neutral trials, because on these trials, attention-related and location-related costs and benefits are in opposition. Again, this was not the case. Although vertical Simon effects were smaller on incompatible than on neutral trials, this reduction was small relative to the Simon-effect increase on compatible trials (16 vs. 33 ms), and for horizontal Simon effects, no reduction at all occurred. (Moreover, recall that for error rates, the opposite pattern—enlarged rather than reduced Simon effects on prime-incompatible trials—was observed.)

In sum, it seems that neither direct interactions of distractor-related inhibitory processes nor prime-induced attentional modulation of target identification can account for the RAE, because both predict mirror-symmetrical effects rather than an effect on only one specific trial type (i.e., not only reduced prime *benefits* on location-incongruent trials, but correspondingly reduced prime *costs* on congruent ones; not only *enlarged* Simon effects on

prime-compatible trials, but correspondingly *reduced* Simon effects on incompatible ones). We therefore propose that the unique feature of this trial type—the back-and-forth alternation of motor responses associated with prime, target location, and target identity—is the cause of the RAE. Specifically, we propose that this back and forth produces confusion at higher-level (metacognitive) processing stages, which results in delayed response execution. This account is based on the assumption that the initial prime-triggered activation registers as incorrect when the target location indicates the opposite response, which then in turn registers as incorrect when the target identity does not correspond with it. Overt response errors are known to be aversive and to produce a reflexive withdrawal response (Hajcak & Foti, 2008; Hochman, Milman, & Tal, 2017). In the case of compatible-incongruent trials, there is no overt error, but all available response options have already proven themselves to be problematic in the face of new evidence. We believe that it is possible that this produces an “aversion” to return to these responses, similar to the aversion produced by overt errors, which manifests as a delay in initiating response activation. In the remainder of this article, we will explore this possibility in more detail.

## Experiment 2: Conscious Awareness

Initial evidence that the RAE might reflect a higher-level process was obtained in SRM11, as only participants who performed the hybrid prime-Simon task with nonmasked (visible) primes produced the RAE, whereas the pattern was absent in participants who performed the task with masked (subliminal) primes. However, although this pattern suggests that conscious awareness of the prime is a necessary precondition for the RAE to occur, this evidence is not conclusive. In those experiments, prime-target ISI was 150 ms (as in Experiment 1 above), and at this interval, masked primes do not produce normal priming effects, but reversed priming effects (NCE, with performance benefits for incompatible and costs for compatible trials relative to neutral trials). The NCE reflects an inhibition of the initially primed response and corresponding disinhibition of the nonprimed response (Eimer & Schlaghecken, 1998; Schlaghecken, Bowman, & Eimer, 2006). Consequently, instead of a sequence of three motor activations (prime → location → target identity), as in the nonmasked prime-Simon task, trials in the masked-prime version elicit a sequence of four (prime → reversal → location → target identity). It is not a priori clear where in this sequence a reactivation-aversion-like effect might occur, if at all: In principle, it might affect the third step (location-triggered activation), the fourth (target-related activation), or both. As a result, it seems conceivable that the RAE was not truly absent in this version of the masked prime-Simon task, but was merely obscured by the intervening reversal phase.

This problem can be avoided by reducing the prime-target ISI. If targets follow the primes immediately, then there is no time for the reversal phase to develop, and normal priming effects occur (Eimer, 1999; Schlaghecken & Eimer, 1997, 2000). The present Experiment 2 therefore used a masked prime-Simon task with a prime-target ISI of 0 ms to investigate the role of prime awareness for the RAE. In particular, we aimed to directly compare performance with subliminal (not consciously available) versus supraliminal primes. Primes were therefore presented either for 16 ms or for 33 ms prior to mask onset (based on pilot data indicating that

with the present set-up, as described below, prime identification performance was near chance with the former and clearly above chance with the latter duration). Like other subliminal perception tasks, masked prime tasks are known to be affected by exposure effects (i.e., experiencing supraliminal primes can change participants' threshold of awareness; e.g., Lamy, Carmel, & Peremen, 2017; Schlaghecken, Blagrove, & Maylor, 2008). To prevent such effects in the present study, prime duration was varied between rather than within participants.

With a 0-ms interval between prime offset and target onset, trials in a masked prime-Simon task elicit the same sequence of three response activations as do trials in the nonmasked version of the task (i.e., prime-triggered activation → location-triggered activation → identity-based activation); the reversal phase developing during longer prime-target ISIs and resulting in the NCE is absent in this design. Consequently, if SRM11 failed to obtain an RAE with masked primes merely because it was obscured by the reversal phase, then in the present experiment, RAEs should occur with both 33-ms (supraliminal) and 16-ms (subliminal) primes. Conversely, if the RAE is a high-level phenomenon that requires conscious awareness of the stimuli involved, then only the former but not the latter duration should produce RAEs.<sup>8</sup>

## Method

**Participants.** Forty-five volunteers from an opportunity sample participated without payment. Three participants were excluded from further analysis due to high overall error rates (>15% valid errors),<sup>9</sup> and one participant was excluded because of failure to follow task instructions, leaving 20 participants in the 16-ms group and 21 in the 33-ms group. According to self-report, participants were 18–32 years old ( $M = 20.8$ ,  $SD = 2.3$ ), eight were male, all but five were right-handed, and all had normal or corrected-to-normal vision.

**Stimuli.** Primes and targets were left- or right-pointing arrows (< and >), and a plus sign (+) served as an additional neutral prime stimulus, all subtending a visual angle of approximately  $2.0^\circ \times 1.5^\circ$  at a viewing distance of approximately 60 cm. Masks were constructed on the basis of a virtual  $9 \times 9$  matrix, randomly filled with overlapping horizontal, vertical and oblique lines of different lengths, resulting in a roughly rectangular array of approximately  $5^\circ \times 3^\circ$ . A new random mask was created on each trial to avoid perceptual learning of the mask and correspondingly increased prime identification (Schlaghecken et al., 2008).

**Procedure.** The experiment consisted of a hybrid prime-Simon task followed by a prime identification task. In the former (see Figure 5, left panel), trials began with a centrally presented prime, followed immediately by a centrally presented mask and a target appearing  $11^\circ$  to the left or right of the center. Prime duration was 16 ms for one group of participants and 33 ms for the other; masks and targets were presented for 100 ms. The ITI was 1,460 ms. All trial types (three prime compatibilities: compatible,

<sup>8</sup> It should be noted that the hybrid prime-Simon RAE has only been observed with prime-target ISIs of more than 100 ms. Thus, a third prediction is that if the RAE requires such longer prime-target ISIs, then no RAE should occur with either 16- or 33-ms primes.

<sup>9</sup> As in Experiment 1, only errors following a correct response were regarded as valid.

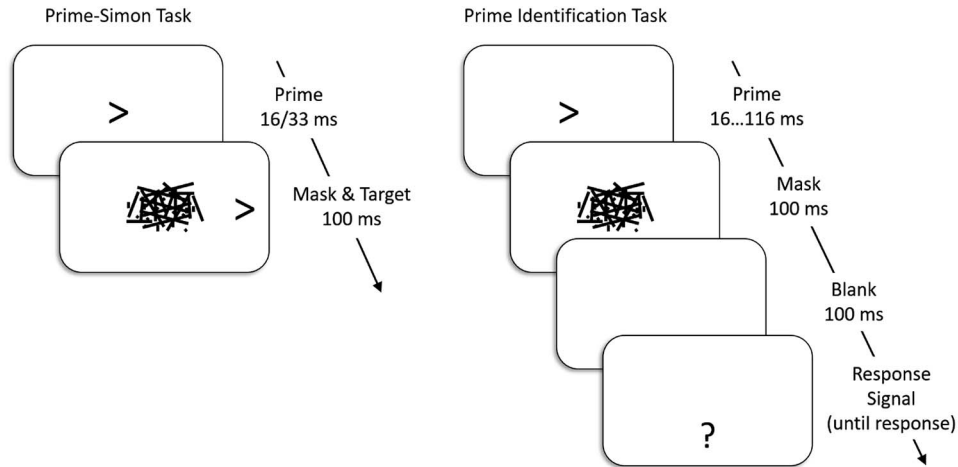


Figure 5. Trial structure in Experiment 2. Left panel: prime-Simon task; right panel: prime identification task.

neutral, incompatible; two target location congruencies: congruent, incongruent; two responses: left, right) were equiprobable and randomized within each block.

In the identification task (see Figure 5, right panel), each trial began with a left- or right-pointing arrow presented randomly and equiprobably for 16, 33, 50, 66, 83, 100, or 116 ms at the center of the screen and immediately followed by a 100-ms mask, but no target. Participants were instructed to indicate the direction of the arrow with corresponding left- or right-hand key presses, and were encouraged to “just guess” in case they failed to consciously identify the stimulus. However, to minimize fast-guess responses (which are most likely to be affected by direct motor priming and therefore are not a useful measure of participants’ conscious prime perception; e.g., Schlaghecken & Eimer, 2006), a question mark (“?”) was presented 100 ms after mask offset below the screen center, and participants were asked not to respond before it had appeared. The question mark remained until a response had been given. The next trial then started 2,000 ms later.

The prime-Simon task consisted of two practice and 10 experimental blocks, containing 60 trials each; the identification task comprised two practice and two experimental blocks of 70 trials each. During practice, the experimenter stayed in the cubicle to ensure that participants had understood and were able to follow the task instructions. Throughout the experiment, participants initiated each block whenever they felt ready to do so. Including instruction, practice, breaks, and debriefing, the experiment took approximately 30 min.

**Data analysis.** As in Experiment 1, only correct RTs and error rates following a correct response were analyzed in the prime-Simon task. Data were grouped into six trial types (3 prime compatibilities  $\times$  2 location congruencies) and analyzed using mixed ANOVAs with the within-subject factors prime compatibility and location congruency and the between-subjects factor prime duration (16/33 ms). Greenhouse-Geisser corrections were applied where appropriate. Interference effects and RAEs were calculated as in Experiment 1 and were analyzed using *t* tests. For the prime identification task, the percentage of correct responses was calculated for each prime duration separately and analyzed with a two-way mixed ANOVA. Follow-up analyses were con-

ducted on 16- and 33-ms primes, using both classical and Bayesian *t* tests.

## Results

**Prime identification task.** Prime identification accuracy increased with increasing prime duration from 56.1% correct responses with 16-ms primes to over 97% correct with primes of 100 and 116 ms duration,  $F(3.43, 133.87) = 98.85, p < .001, MSE = 169.61, \eta_p^2 = .717$  (see Figure 6). There was no main effect of group, nor a Group  $\times$  Duration interaction, both  $F_s < 1.7$ , both  $ps > .12$ , both  $\eta_p^2_s < .05$ . However, planned *t* tests revealed that identification performance for 16-ms primes was indistinguishable from chance in the 16-ms group (52.3%;  $t(19) < 1; BF_{01} = 3.37$  at a Cauchy prior width of 0.707), but significantly above chance in the 33-ms group (60.0%;  $t(20) = 3.18, p = .005$ ). Both groups correctly identified 33-ms primes significantly above chance level (78.0% and 77.9% accuracy for the 16-ms and 33-ms groups, respectively, both  $t_s > 7.8$ , both  $ps < .001$ ).

**Hybrid prime-Simon task.** Error rates showed both priming effects (8.0, 10.7, and 11.9% errors with compatible, neutral, and incompatible primes, respectively),  $F(1.60, 62.36) = 37.75, p < .001, MSE = 19.62, \eta_p^2 = .492$ , and Simon effects (4.4% and 13.3% with congruent and incongruent target locations, respectively),  $F(1, 39) = 147.68, p < .001, MSE = 33.00, \eta_p^2 = .791$  (see Figure 7). These two factors interacted, as Simon effects were smallest with compatible primes (6.1%), intermediate with neutral primes (8.3%), and largest with incompatible primes (12.3%),  $F(2, 78) = 33.83, p < .001, MSE = 6.15, \eta_p^2 = .465$ . There was no main effect of group, nor any significant interactions with this factor, all  $F_s < 2.31$ , all  $ps > .10$ , all  $\eta_p^2_s < .06$ .

RTs similarly showed both priming effects (427, 437, and 445 ms with compatible, neutral, and incompatible primes, respectively),  $F(1.64, 64.09) = 56.80, p < .001, MSE = 252.78, \eta_p^2 = .593$ , and Simon effects (418 and 459 ms with congruent and incongruent target locations, respectively),  $F(1, 39) = 152.05, p < .001, MSE = 612.49, \eta_p^2 = .796$ . These factors did not interact,  $F < 1$ . There was no main effect of group,  $F(1, 39) = 1.26, p = .268, MSE = 9,048.26, \eta_p^2 = .031$ ,

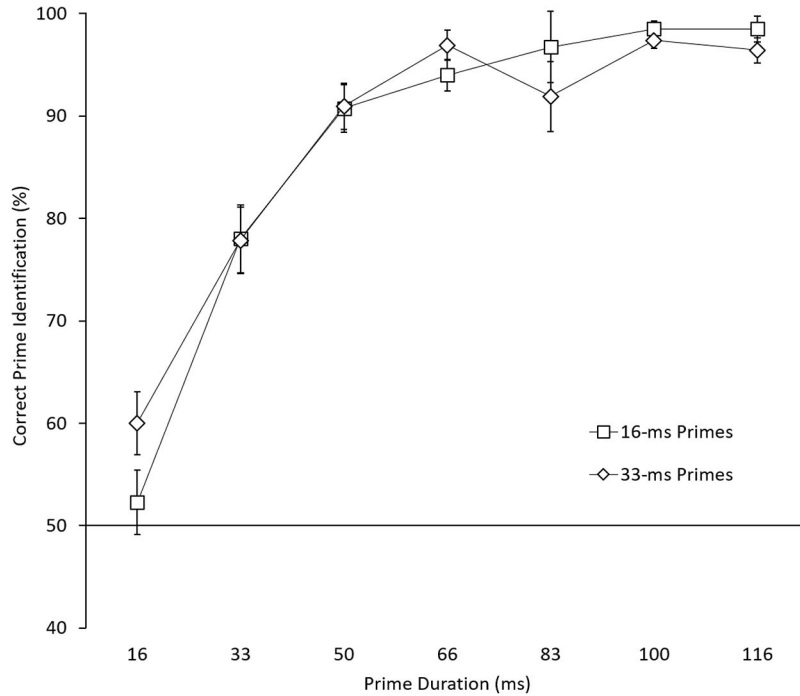


Figure 6. Prime identification performance in Experiment 2, separately for participants who performed the Prime × Simon task with 16-ms primes (squares) and 33-ms primes (diamonds). Error bars represent ±1 SEM.

and no interaction between group and location congruency,  $F < 1$ . However, priming effects were larger in the 33-ms group than in the 16-ms group,  $F(2, 78) = 12.59, p < .001, MSE = 207.71, \eta_p^2 = .244$ , although follow-up ANOVAs, conducted for

each group separately, confirmed that they were significant in both groups,  $ps < .001$ .

Most importantly, as can be seen in Figure 7, the 33-ms group produced an RAE, whereas the 16-ms group did not, reflected in a

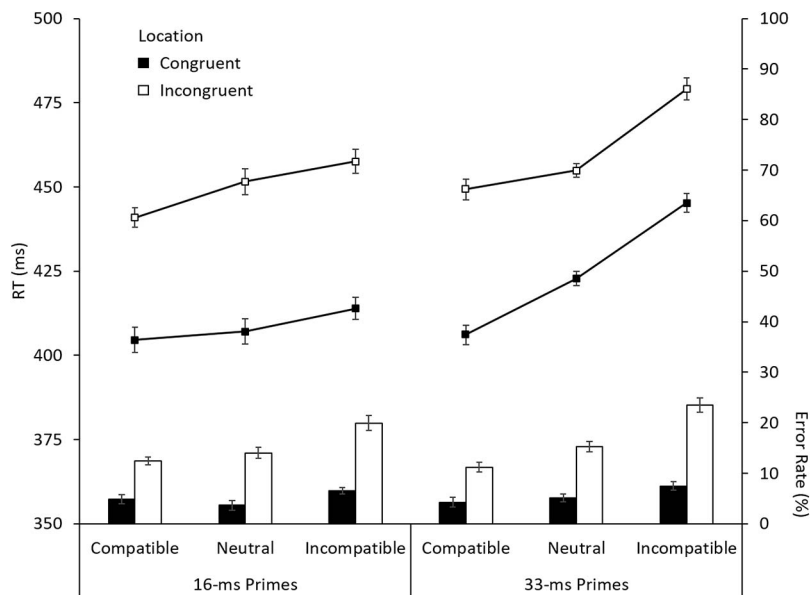


Figure 7. Response times (RTs; lines) in milliseconds (ms) and percentage error rates (bars) in Experiment 2 as a function of prime compatibility, plotted separately for the two prime duration groups, and for congruent (black) and incongruent (white) target locations (note that the RT scale differs from Figures 3 and 9). Error bars represent ±1 SEM after removal of between-subjects variability (Cousineau, 2005), calculated for each group separately.

significant prime-Location  $\times$  Group interaction,  $F(2, 78) = 6.02$ ,  $p = .004$ ,  $MSE = 92.43$ ,  $\eta_p^2 = .134$ . Follow-up analyses, comparing Simon effects between the different prime-type trials separately for each group, confirmed this pattern: The 33-ms group showed a normal RAE, with larger Simon effects on compatible than on neutral trials (43 vs. 32 ms),  $t(20) = 2.49$ ,  $p = .022$ , whereas in the 16-ms group, Simon effects were numerically—though not statistically—smaller on compatible than on neutral trials (36 vs. 45 ms),  $t(19) = 1.99$ ,  $p = .061$ . Neutral- and incompatible-trial Simon effects were statistically indistinguishable from each other in both groups, both  $t_s < 1$ .

Arguably, this difference—the presence of the RAE with 33-ms primes and its absence with 16-ms primes—might not be due to the difference in these primes' availability to conscious awareness, but rather to the fact that priming effects were significantly larger with 33- than with 16-ms primes. To test this possibility, we conducted a median split of priming effects for each group separately (based on priming effects on location-congruent trials, to avoid confounding priming effects and RAEs), and calculated RAEs (Simon effect on compatible trials minus Simon effect on neutral trials) for each subgroup separately. The results are displayed in Figure 8, which clearly shows that the magnitude of priming effects cannot account for the presence or absence of the RAE: "Large" priming effects in the 16-ms prime group were virtually identical in size to "small" priming effects in the 33-ms prime group, yet only the latter produced the RAE (highlighted by the dashed oval in Figure 8). These results strongly suggest that it is prime visibility itself, not magnitude of priming effects, that determines the presence or absence of RAEs.

## Discussion

Experiment 2 investigated whether the RAE pattern—an enlarged Simon effect on prime-compatible trials relative to prime-neutral and prime-incompatible trials, or correspondingly, reduced prime benefits on location-incongruent relative to congruent trials—occurs when primes are successfully masked and thus unavailable to conscious awareness. If it does, then this would suggest that the RAE reflects relatively low-level visual-attentional or motor inhibitory processes directly tied to prime processing. Conversely, if no RAE occurs with subliminal primes (but does occur with similarly masked but supraliminal ones), then this would suggest that it reflects subsequent higher-level or metacognitive processes. The present results support the second proposition by demonstrating that the RAE is, indeed, linked to whether or not primes are successfully masked: Whereas supraliminal primes produced a robust RAE, this pattern was absent for subliminal primes (in fact, the latter produced a numerically, though not statistically, reversed pattern).

Although this result fits with the prediction of the "metacognitive confusion" or "aversion" hypothesis, some caveats are in order. First, prime identification performance in a subsequent forced-choice test can only provide an approximation of participants' conscious awareness of the primes during the prime-Simon task. In principle, forced-choice identification might underestimate the level of awareness during the critical task (i.e., participants in the 16-ms group might have been aware of the primes at the time even if they were subsequently unable to successfully identify them). In practice, however, it seems more likely that it overesti-

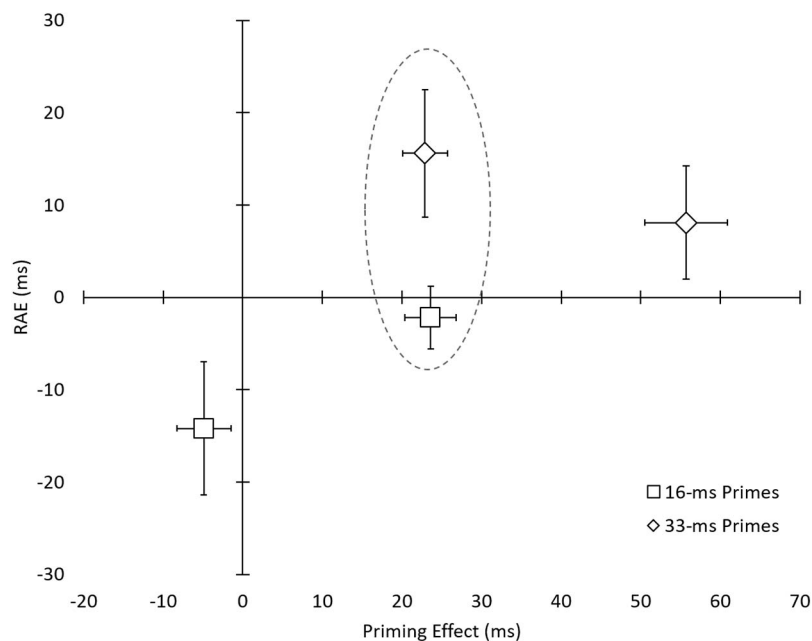


Figure 8. Reactivation aversion effect (RAE; Simon effect on compatible trials minus Simon effect on incompatible trials) in milliseconds (ms) as a function of priming effect magnitude, plotted separately for participants in the 16-ms prime group (squares) and 33-ms prime group (diamonds). Error bars represent  $\pm 1$  SEM. The dashed oval marks the relevant comparison between RAEs of 16-ms participants with large, and 33-ms participants with small, priming effects.

mates the level of awareness, as during the identification task, participants focus on the primes and actively try to identify them, whereas during the prime-Simon task, they focus on the—subsequently presented and laterally displaced—targets. Consequently, during the prime-Simon task, 33-ms masked primes might have been less available to conscious awareness than the prime identification performance suggests. It is therefore important to distinguish between the participants' subjective experience of the prime and the stimulus conditions that contribute to this experience: The present experiment can only directly demonstrate a functional role of the latter, not the former, for the RAE.

A second issue, related to the first, is that there is no generally accepted definition of “consciousness” and related concepts, and consequently few firmly established facts about its function or underlying mechanisms (e.g., Zeman & Coebergh, 2013). For instance, recent research has demonstrated that even when participants cannot identify masked primes, they still can tell “easy” (compatible) from “difficult” (incompatible) trials with better than chance accuracy (e.g., Desender, Van Opstal, & Van den Bussche, 2014, 2017). These results appear to undermine our argument that the RAE reflects “metacognitive confusion”: If subliminal primes are available to metacognition, then should they not have produced an RAE? However, it is important to note that in Desender et al.'s studies, participants had to deliberately direct their attention to “feelings of difficulty” in order to perform the task. Such top-down attention amplifies neural signaling (e.g., Alais & Blake, 1999; Treue & Martínez Trujillo, 1999), and this amplification affects not only supraliminally triggered signals, but also, unsurprisingly, signals triggered subliminally (e.g., Forschack, Nierhaus, Müller, & Villringer, 2017; Kiefer & Martens, 2010). Consequently, the fact that participants attending to subtle sensorimotor signals can gain metacognitive awareness of these signals does not imply that such metacognitive awareness exists “spontaneously,” in the absence of attentional amplification, as in the present experiment. It would be interesting to investigate this issue directly in future research by asking participants in a subliminal prime-Simon task to rate each trial's difficulty (as in Desender et al.'s studies). If the above reasoning is correct, then metacognitive awareness should emerge, and with it, the RAE.

A third issue to consider is the possibility that there might be further qualitative differences between supraliminal and subliminal stimulation. Of particular relevance in the current context, several studies have demonstrated that subliminal stimuli fail to elicit CSEs (e.g., Ansoorge, Fuchs, Khalid, & Kunde, 2011; El Karoui, Christoforidis, & Naccache, 2017; SRM11);<sup>10</sup> thus either CSEs, like the RAE, require conscious awareness, or subliminally triggered sensorimotor activations differ fundamentally from supraliminally triggered ones. In either case, the present result of an absent RAE with subliminal primes would not be informative with regard to the paradox of between-trial domain-specificity and within-trial domain interactions in sensorimotor interference tasks. However, it is possible that those findings are the exception rather than the rule, as numerous studies have reported robust CSEs elicited by subliminal stimuli (e.g., Huber-Huber & Ansoorge, 2017, 2018; Jiang, Correa, Geerts, & van Gaal, 2018; Schoupe, de Ferrer, Van Opstal, Braem, & Notebaert, 2014), if not in RTs then in error rates (e.g., Atas, Desender, Gevers, & Cleeremans, 2016; Hasegawa & Takahashi, 2014). Given these mixed results, the question of whether or not results from subliminal priming can

resolve the RAE paradox cannot be answered conclusively. In order to obtain converging evidence, we therefore turned to a fundamentally different approach: the investigation of individual differences.

### Experiment 3: Aging

After the third decade, the nervous system deteriorates both anatomically and biochemically (for reviews, see Mohan, Mather, Thalamuthu, Baune, & Sachdev, 2016; Rossini, Rossi, Babiloni, & Polich, 2007). Correspondingly, many sensory, cognitive, and motor processes decline from young adulthood to old age (for overviews, see Hofer, Berg, & Era, 2003; Roberts & Allen, 2016). One of the challenges for aging research is therefore to establish whether, against the background of such general decline, any specific functions are particularly impaired. Perhaps surprisingly, the control of sensorimotor interference appears to remain mostly intact across the life span: Once older adults' generally slower processing (see Cerella, 1985; Salthouse, 1996) has been taken into account, most interference effects tend to be of similar magnitude in young and older adults. Importantly, such age equivalence occurs not only for simple sensorimotor interference effects like Stroop or flanker effects. Rather, it also occurs for so-called inhibitory aftereffects, that is, for effects that originate from the reactivation of an automatically activated but then discarded response such as antisaccade delays, NP, IOR, and local switch and N-2 repetition costs (for reviews and meta-analyses, see, e.g., Gamboz, Russo, & Fox, 2002; Rey-Mermet & Gade, 2018; Rey-Mermet, Gade, & Oberauer, 2018; Verhaeghen, 2011, 2014), and spatial NP (Buckolz, Lok, Kajaste, Edgar, & Khan, 2015). Moreover, in tasks in which older adults do appear disproportionately disadvantaged, the age-related deficit takes the form of delayed or reduced aftereffects, such as with IOR onset (Erel & Levy, 2016) and the NCE with subliminal primes (Maylor, Birak, & Schlaghecken, 2011; Schlaghecken, Birak, & Maylor, 2011, 2012; Schlaghecken & Maylor, 2005). In short, in older adults, low-level sensorimotor processes that resemble the back-and-forth of compatible-incongruent trials in the hybrid prime-Simon tasks appear to be mostly intact (or rather, not specifically impaired), and where specific age-related deficits do occur, they result in delayed or reduced sensorimotor interference effects. Thus, if the RAE similarly reflects sensorimotor interference, it should correspondingly be age-equivalent or reduced in older compared with young adults.

In contrast, the efficiency of high-level monitoring and decision processes declines with age over and above the effects of general slowing. This shows in older adults' disproportionately enlarged dual-task costs and global (as opposed to local) switch costs, both attributed to an age-related specific difficulty in scheduling two tasks at once or switching the focus of attention in working memory (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Reimers

<sup>10</sup> Sequential analysis of the present experiment—analogue to Experiment 1—failed to show prime-triggered CSEs in either group, both  $F_s < 1.2$ , both  $p_s > .3$ . However, due to the small number of valid trials in each condition (12 on average) and the comparatively large variation of trial numbers across conditions (means ranging from 9 to 17), reliable statistical results would require substantially greater numbers of participants (i.e., approximately 2.5 times as many participants in each group, corresponding to Experiment 1).

& Maylor, 2005; for reviews and meta-analyses see Jaroslawska & Rhodes, 2019; Verhaeghen, 2011, 2014; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). It also shows in the types of errors older adults make when interpreting so-called garden-path sentences (Malyutina & den Ouden, 2016) and their disproportionate difficulties in parsing sentences with double negatives (e.g., Yoon et al., 2015), both requiring “mental backtracking” and reanalyzing already-processed information. Consequently, if the RAE reflects similar high-level confusion, we should expect it to be disproportionately enlarged in older compared with young adults.

**Method**

**Participants.** Twenty-three young and 28 older adults participated in Experiment 3. To obtain groups with similar performance levels, we excluded participants with more than 15% errors and/or fewer than 66% valid correct trials, leaving a final sample of 21 young adults (18–30 years; seven male; no left-handers) and 19 older adults (64–82 years; eight male; three left-handers).<sup>11</sup> The former were students from the University of Warwick who took part either for course credit or £6 (\$7); the latter were members of a volunteer panel recruited through local newspapers and advertisements who were paid £10 (\$12) as a contribution toward their travel expenses. Background cognitive measures were already available for older participants from earlier testing sessions, and were collected from young participants immediately after completing the present experiment. Demographic and background data are listed in Table 4. As expected (cf. Salthouse, 1991), young adults had poorer vocabulary but better speed and visual acuity than did older adults.

**Stimuli.** As in SRM11, primes and targets were double arrows (<< and >>), subtending a visual angle of 2.0° × 0.9°. To achieve sufficient numbers of valid trials per condition, in particular in older adults, no neutral primes were presented in this experiment. To keep stimulus conditions as similar as possible to another task carried out in the same session (see below), an empty rectangular “frame” measuring 2.6° × 1.4° was presented between the prime and the target. Primes and frames appeared at the center

of the screen, and targets appeared 5.7° to the left or right of the center. Viewing distance was approximately 100 cm.

**Procedure.** Participants were seated in a comfortable chair with response buttons mounted onto the arm rests. The experimental session lasted approximately 1 hr, during which participants carried out two different hybrid prime-Simon tasks (with task order counterbalanced across participants). One task addressed the issue of age-related dedifferentiation and deautomatization of inhibitory control and has been published elsewhere (see Maylor et al., 2011). The other, reported here, investigated age-related changes in the RAE. It consisted of six experimental blocks, each containing 72 trials, preceded by one practice block of 32 trials. To help particularly older participants to maintain central fixation, a central 250-ms fixation dot (0.1° × 0.1°) was presented before each prime, followed by a 650-ms blank screen. Next, a prime was presented for 33 ms, followed by the frame for 100 ms, a 50-ms blank, and finally a target, presented for 100 ms. The ITI between target offset and the next fixation dot was 1,300 ms. Participants were instructed to maintain central eye fixation throughout, and to respond as quickly and accurately as possible to the direction of the target arrows (i.e., a left-hand key-press to left-pointing arrows, and a right-hand key-press to right-pointing arrows), regardless of the target’s location on the screen. All trial types (2 prime compatibilities × 2 target location congruencies × 2 responses) were equiprobable and randomized within each block.

**Data analyses.** As before, only RTs and errors following a correct response were analyzed (93.1% of all correct responses, 88.3% of all errors). Data were grouped into four trial types (2 prime compatibilities × 2 location congruencies) and analyzed using mixed ANOVAs with the within-subject factors prime compatibility and location congruency and the between-subjects factor age group (young, older). In order to account for the effect of general age-related slowing, RT priming and Simon effects were calculated not as differences, but as ratios;<sup>12</sup> the RAE was calculated as the difference between Simon effects on prime-compatible and prime-incompatible trials. Follow-up analysis of interference effects and RAEs were conducted using *t* tests.

**Results**

RTs and error rates are depicted in Figure 9, and the corresponding ANOVA results are listed in Table 5. Older adults responded overall 156 ms slower than did young adults but

Table 4  
*Background Details (Means and Standard Deviations) of Young and Older Participants Included in Experiment 3, and Results of Comparisons Between Age Groups*

Variable	Young ( <i>n</i> = 21)	Older ( <i>n</i> = 19)	Comparison
	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )	
Age (years)	20.4 (3.2)	70.1 (4.9)	—
Vocabulary <sup>a</sup>	17.3 (3.9)	24.7 (4.0)	<i>t</i> (37) = 5.87, <i>p</i> < .001
Speed <sup>b</sup>	74.4 (9.7)	54.1 (9.8)	<i>t</i> (37) = 6.50, <i>p</i> < .001
Visual acuity <sup>c</sup>	6.52 (1.0)	5.32 (1.3)	<i>t</i> (38) = 3.28, <i>p</i> = .002

<sup>a</sup> Vocabulary from the multiple choice section of the Mill Hill vocabulary test (Raven, Raven, & Court, 1988); maximum score = 33; data missing for one young participant. <sup>b</sup> Processing speed based on the digit symbol substitution task (Wechsler, 1981); data missing for one young participant. <sup>c</sup> Visual acuity as measured by the number of lines read correctly from the Near Vision Test Card (Schneider, 2002) viewed at a distance of 16 in. while wearing corrective glasses, with scores ranging from 1 (16/160 = lowest acuity) to 9 (16/16 = highest acuity).

<sup>11</sup> We also analyzed the data using more lenient exclusion criteria (error-rate cut-offs of 20%, leaving 23 young and 21 older adults, and of 30%, leaving 23 young and 25 older adults), which produced qualitatively similar though noisier patterns of results.

<sup>12</sup> For instance, assume that older adults are generally 1.5 times slower than young adults: Task A, taking young adults 300 ms, will take older adults 450 ms, and Task B, taking young adults 400 ms, will take older adults 600 ms. As a result, young adults will have a B–A effect of 100 ms, older adults one of 150 ms—an increase in magnitude that seems to suggest a specific age-related deficit in B-processing where in fact none exists. Using RT ratios avoids this problem (here: 400/300 = 1.3, 600/450 = 1.3, correctly indicating that there is no additional B-processing deficit in older adults; see, e.g., Verhaeghen, 2011). An alternative to calculating proportional effects/ratios is to transform the data using z-scores (see Faust, Balota, Spieler, & Ferraro, 1999; Hedge, Powell, & Sumner, 2018a). These two methods led to identical conclusions; we report ratios here but include z-scores in the online supplemental materials.



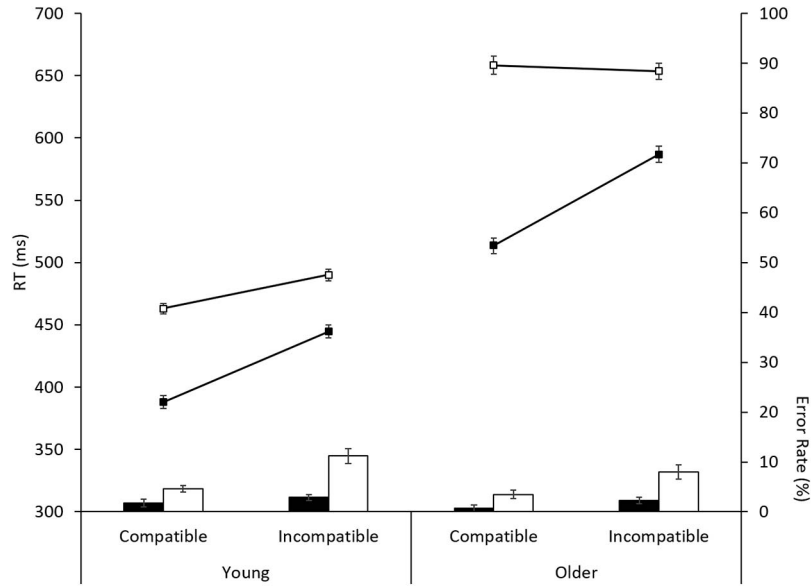


Figure 9. Mean correct response times (RTs; lines) in milliseconds (ms) and percentage error rates (bars) on prime-compatible and prime-incompatible trials in Experiment 3, plotted separately for young and older adults, and for location-congruent (black) and location-incongruent (white) trials. Error bars represent  $\pm 1$  SEM after removal of between-subjects variability (Cousineau, 2005), calculated separately for each age group.

produced virtually identical error rates (both 5.8%). Responses were 38 ms faster and 3.3% points more accurate for compatible than for incompatible primes, and 83 ms faster and 5.6% points more accurate for congruent than for incongruent target locations. Whereas RT priming effects were similar across age groups, RT Simon effects were significantly larger in older than in young adults (106 vs. 60 ms). Prime compatibility and location congruency interacted for both RTs and error rates, and again, as in the previous two experiments, did so in opposite directions: For RTs, the Simon effect was larger with compatible than with incompatible primes (110 vs. 56 ms; RAE), whereas for error rates, the reverse was true (4.0% vs. 7.3%). For RTs, but not for error rates, the prime-Location interaction was modulated by age group, as older adults' RAE (i.e., compatible minus incompatible Simon effect) was more than twice as large as that of young adults (78 vs. 30 ms).

Given the large overall RT difference between young and older participants, it is essential to investigate whether these interactions remain after general slowing has been taken into account, that is, when effects are calculated as RT ratios. As can be seen in Figure 10, neither priming nor Simon effects differed between young and older adults on trials that were not affected by the RAE (i.e., priming effects on location-congruent trials and Simon effects on prime-incompatible trials, both  $t(38) < 1$ ). In contrast, priming effects on incongruent trials were significantly reduced, and Simon effects on prime-compatible trials were significantly enlarged in older compared with young adults,  $t(38) = 2.71$ ,  $p = .010$ , and  $t(38) = 2.99$ ,  $p = .005$ , respectively. Most importantly, after taking general slowing into account, the RAE was still almost twice as large in older than in young participants (0.172 vs. 0.095;  $t(38) = 3.23$ ,  $p = .003$ ).<sup>13</sup>

## Discussion

The aim of Experiment 3 was to directly contrast the sensorimotor interference and high-level confusion hypotheses of the RAE by investigating whether older adults produce an age-equivalent (or even reduced) RAE or a disproportionately enlarged one. The results were clear-cut: Far from being age-equivalent, older adults' RAEs were almost double in size compared with those of young adults, even though (a) participants had been selected to ensure similar levels of overall performance; (b) age-related slowing had been partialled out; and (c) interference effects on RAE-unrelated trials (priming effects on location-congruent trials, Simon effects on prime-incompatible trials) were indistinguishable between the two age groups. This pattern of results matches the predictions of the high-level confusion hypothesis, and conflicts with the predictions of the sensorimotor interference hypothesis. Therefore, it strongly supports the notion that the RAE

<sup>13</sup> We also conducted a CSE analysis on ratio effects, which confirmed the presence of domain-specific effects. An interaction between the previous and current trial's location-congruency for priming effects, suggesting at least partial domain-general CSEs, was in fact accounted for by RT differences between these trials: Time-course analysis confirmed that priming effects had a negative-going latency slope (decreasing substantially with increasing response latency), and that the interaction was entirely accounted for by the fact that congruent trials were faster (and correspondingly had larger priming effects) following congruent than following incongruent trials, whereas the reverse was true for incongruent trials. CSEs did not differ between age groups but, as with Experiment 2, the numbers of valid trials were rather small for at least some conditions and participants. Consequently, these patterns should be considered suggestive rather than conclusive.

Table 5  
ANOVA Results for Response Times and Error Rates in Experiment 3

Factors	Effects			MSE	× Age group		
	<i>F</i> (1, 38)	<i>p</i>	$\eta_p^2$		<i>F</i> (1, 38)	<i>p</i>	$\eta_p^2$
Response time							
Age group	90.29	<b>&lt;.001</b>	.704	10806.46	—	—	—
Prime	40.95	<b>&lt;.001</b>	.519	1404.21	<1	.531	.010
Location	286.56	<b>&lt;.001</b>	.883	960.08	21.51	<b>&lt;.001</b>	.361
Prime × Location	131.80	<b>&lt;.001</b>	.776	219.95	26.55	<b>&lt;.001</b>	.411
Error rate							
Age group	<1	.998	<.001	70.91			
Prime	14.63	<b>&lt;.001</b>	.278	29.64	<1	.583	.008
Location	49.41	<b>&lt;.001</b>	.565	25.76	<1	.853	.001
Prime × Location	5.51	<b>.024</b>	.127	20.40	2.31	.137	.057

Note. Significant *p* values highlighted in bold.

does not originate at direct sensorimotor processing stages, but reflects processing difficulties at a higher or subsequent level.

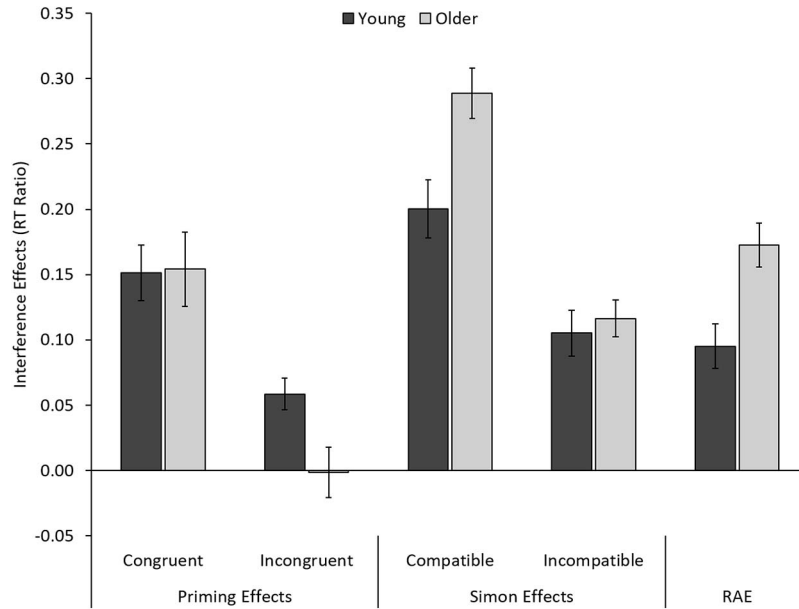
The finding of age-equivalent priming and Simon effects in both RTs and error rates is in line with the notion that aging is not associated with a general executive control deficit. Specifically, the age-equivalent priming effects confirm findings from masked priming (Schlaghecken, Birak, et al., 2011; Schlaghecken & Maylor, 2005) and flanker tasks, which show little if any age-related differences (Rey-Mermet & Gade, 2018; Rey-Mermet et al., 2018; Verhaeghen, 2011, 2014). Together, these results suggest that older adults' ability to inhibit motor activity triggered by target-like distractor stimuli is not selectively impaired. In contrast, the age-equivalent Simon effects observed here appear to conflict with results showing disproportionately enlarged Simon effects in older compared with young participants (e.g., Castel, Balota, Hutchison, Logan, & Yap, 2007; Maylor et al., 2011; van der Lubbe & Verleger, 2002), which have been taken to suggest a selective impairment in older adults' ability to inhibit location-triggered automatic motor activations. However, Aisenberg, Sapir, d'Avossa, and Henik (2014) demonstrated that this age effect disappears when ITIs are increased, indicating that aging does not impair location-related sensorimotor inhibition as such, but increases the time needed to "reformulat[e] current behavioral strategies" (p. 169). Furthermore, age-related differences in Simon effect magnitude are eliminated when frequent no-go trials are added to the task, possibly because in such a task context, participants implement a tonic suppression of fast, automatic response activations (Kubo-Kawai & Kawai, 2010). It seems plausible that in the present task, the additional inhibitory requirement of not responding to the prime might have produced a similar effect.<sup>14</sup>

Against this background of age-equivalent interference effects, the age-related difference in RAE magnitude is particularly striking. The pattern strongly suggests that the RAE does not result from sensorimotor inhibition, which is mostly spared in old age (Rey-Mermet & Gade, 2018; Rey-Mermet et al., 2018; Verhaeghen, 2011, 2014), but instead reflects difficulties at higher levels, presumably involving mental backtracking and reassessing already-processed information, which often show age-related deficits (Verhaeghen, 2011, 2014; Wasylyshyn et al., 2011).

## General Discussion

The present study set out to investigate an apparent paradox in cognitive control. On the one hand, studies of between-trial CSEs typically suggest that separate, domain-specific mechanisms control the activation and inhibition processes associated with different types of distractors (Akçay & Hazeltine, 2011; Egner et al., 2007; Forster & Cho, 2014; Funes et al., 2010; Kim et al., 2012; SRM11; Wendt et al., 2006; for reviews, see Braem et al., 2014; Duthoo et al., 2014a, 2014b; Egner, 2008, 2017). Correspondingly, one would expect that studies employing hybrid interference tasks (i.e., tasks in which two different types of distractors are present simultaneously) would find additive (noninteractive) effects within each trial. Although this pattern has indeed been observed (for overviews, see Rey-Mermet & Gade, 2016, and Table 1), it is, unexpectedly, not the norm. Rather, such studies often find that RTs show underadditive within-trial interactions between distractor domains (see Table 2), suggesting shared control mechanisms. The question of whether control mechanisms are domain-specific or domain-general is of central importance in the field (e.g., Braem et al., 2014; Duthoo et al., 2014a, 2014b; Egner, 2008, 2017), affecting not only theories of cognitive control, but also the understanding of normal versus impaired control processes in developmental and clinical psychology. It is therefore surprising that

<sup>14</sup> In particular, the results suggest that this improvement depends on "conscious" or high-level mechanisms. In a masked prime task, the prime is subliminal and not available to conscious perception. Consequently, participants are not aware of the need to inhibit a response to it (and automatic inhibition of subliminally triggered motor activations is indeed impaired in older adults; see Maylor et al., 2011; Schlaghecken et al., 2011, 2012; Schlaghecken & Maylor, 2005). In the present experiment, in contrast, as well as in the Kubo-Kawai and Kawai (2010) study, the relevant stimuli (primes and no-go-targets, respectively) were fully visible, and participants were in fact explicitly instructed not to respond to them. It is tempting to argue that such intentional inhibition, mediated by dorsal fronto-median cortex (e.g., Ficarella & Battelli, 2017), provides a top-down "boost" to low-level sensorimotor inhibition, and that this might be particularly true for older adults, who have been shown to "shift" activation from posterior to more anterior cortical areas, especially under increased cognitive load (e.g., Ansado, Monchi, Ennabil, Faure, & Joannette, 2012). However, there is as yet not enough evidence available in support of this conjecture, and further research is needed to explore this issue more directly.



*Figure 10.* Interference effects (response time [RT] ratios) for young (dark gray) and older (light gray) participants in Experiment 3. Priming effects are plotted separately for trials with congruent/incongruent target locations; Simon effects are plotted separately for trials with compatible/incompatible primes. Priming and Simon effects are expressed as RT ratios (e.g., priming = incompatible RT/compatible RT; for convenience, 1 is subtracted from the result so that 0 indicates that values are the same); RAE (reactivation aversion effect) = compatible-trial Simon effect minus incompatible-trial Simon effect. Error bars represent  $\pm 1$  SEM.

relatively few studies have addressed within- and between-trial interactions simultaneously (see the two right-most columns of Tables 1 and 2). In particular, as far as we are aware, no study to date has addressed this issue in a hybrid task free of repetition and contingency confounds.

Experiment 1 confirmed that the “paradoxical” interference pattern occurs within a single, confound-free design. In a hybrid prime-Simon task, trial-by-trial modulations of interference effects were domain-specific (i.e., a trial’s prime compatibility affected priming effects, but not Simon effects, on the next trial, whereas a trial’s target-location congruency affected subsequent Simon but not subsequent priming effects), suggesting that distractor-related processing and control occurs within separate, domain-specific sensorimotor pathways. At the same time, interference effects interacted within each trial, such that Simon effects were larger with compatible than with neutral or incompatible primes, or correspondingly, prime benefits were smaller with incongruent than with congruent target locations. The inclusion of neutral primes allowed us to establish that this interaction resulted from a selective response slowing on prime-compatible location-incongruent trials (see Figure 3). We argued that neither sensorimotor interactions nor attentional “enhancements” of sensorimotor processing produce the slowing on prime-compatible location-incongruent trials, but that it arises instead from difficulties beyond sensorimotor processing stages that are unique to this particular trial type.

The feature that sets compatible-incongruent trials apart from other trial types is that they contain a back-and-forth sequence of response triggers (see Figure 1). Such a sequence might not affect activation and/or inhibition within each (domain-specific) senso-

rimotor channel. However, to a high-level or metacognitive action monitoring system, it presents as a series of not merely conflicting (“go right—no, go left”) but self-contradicting instructions (“go right—no, go left—no, go right after all”). We argued that similar to awareness of overt response errors (Hajcak & Foti, 2008; Hochman et al., 2017), awareness of these self-contradictions is likely to cause confusion and a reluctance to reactivate any of the previously discarded responses.

If this high-level interpretation of the RAE is correct, then minimizing access to high-level or “aware” processing should minimize the RAE, and maximizing high-level confusability should maximize it. Experiments 2 and 3 directly investigated these predictions. Using a masked prime-Simon paradigm, Experiment 2 confirmed that the RAE is associated with conscious awareness. Whereas supraliminal masked primes (i.e., primes that could be identified with above-chance accuracy) produced an RAE, this effect disappeared with subliminal primes (i.e., primes that were not available to conscious awareness, as evidenced by chance-level identification performance). This result is in line with the high-level confusion account, and conflicts with low-level sensorimotor inhibition and automatic attentional shift accounts: Similar to supraliminal stimuli (though perhaps more strongly dependent on top-down contingencies), subliminal stimuli can trigger automatic sensorimotor processes (e.g., D’Ostilio, Collette, Phillips, & Garraux, 2012; Eimer & Schlaghecken, 1998; McBride, Sumner, & Husain, 2018; Praamstra & Seiss, 2005; Schlaghecken & Eimer, 2004) and shifts of visual spatial attention (e.g., Palmer & Mattler, 2013; Reuss, Pohl, Kiesel, & Kunde, 2011; for a review, see Ansorge, Kunde, & Kiefer, 2014). In contrast, stimuli or events of which we are not aware seem to have

little if any effect on such processes as shifting internal attention in working memory or setting up a new task-set (e.g., Janczyk & Reuss, 2016; Schlaghecken & Eimer, 2004), or indeed delaying response execution following an error (Klein et al., 2007). Consequently, if the RAE reflects such automatic sensorimotor or attentional processes, it should have been found regardless of conscious prime awareness. The fact that it was not suggests that the RAE is not triggered by the compatible-incongruent trials' features as such (that is, not by low-level sensorimotor processing of these features), but rather by the participant's awareness of the self-contradictory nature of these features and/or their associated sensorimotor processes.

However, not only are there several caveats attached to subliminal stimulation studies (as discussed above), it is also clear that evidence from absence necessarily remains inconclusive. Experiment 3 therefore sought to establish additional evidence for the high-level confusion hypothesis in a context in which the high-level confusion account predicts enlarged RAEs, whereas low-level interference accounts predict unaltered or reduced RAEs. Thus, we compared performance in a hybrid (nonmasked) prime-Simon task between young and older adults: If the RAE reflects an aftereffect of sensorimotor inhibition, it should be age equivalent or reduced in older compared with young adults, whereas if it reflects high-level confusion, it should be disproportionately enlarged in older adults. Again, results were unambiguous: Although older adults produced overall longer RTs, their priming and Simon effects were of equivalent magnitude to those of young adults, confirming that sensorimotor inhibition is not selectively impaired by aging. The same appeared to be true for CSEs, which were of similar magnitude and equally domain-specific for young and older adults—however, as noted above, the relatively low number of trials per condition coupled with the relatively small number of participants renders this result suggestive rather than conclusive.<sup>15</sup> Importantly, however, despite the overall similarity of performance, older adults produced disproportionately increased RAEs, in line with the high-level confusion account and in direct contradiction of low-level sensorimotor accounts.

### RAE in Context

Together, the present results demonstrate that an apparently fundamental paradox in cognitive control—namely, control processes appearing to be simultaneously domain-specific (as evidenced by a lack of between-trial interactions) and domain-general (as evidenced by the presence of an underadditive within-trial interaction)—is not paradoxical after all. The evidence suggests that whereas interference effects and CSEs primarily reflect sensorimotor processes within separate, domain-specific pathways, the apparent domain-general within-trial interaction in reality reflects confusion at subsequent (higher-level or metacognitive) processing levels, induced by a specific self-contradictory sequence of events.

The extent to which this explanation applies to situations other than the specific conditions of an arrow-based prime-Simon task is of course an empirical question that requires further investigation. However, our account seems to fit results from various other hybrid interference paradigms. For instance, in studies using hybrid flanker-Simon paradigms (see Table 2, top), flanker effects are typically smaller on location-incongruent than on location-

congruent trials. Whereas in the present experiments, the RAE was driven by a delay on prime-compatible location-incongruent trials, it seems likely that in flanker-Simon paradigms, it is driven by a delay on flanker-incompatible location-congruent trials, because location processing is faster than identity processing (Cespón, Galdo-Álvarez, & Díaz, 2013; Finkbeiner & Heathcote, 2016). Consequently, in these tasks, the first “instruction” would come from the stimulus location (*left*), the second from the flankers (*no, right*), and the final one from the target itself (*no, left after all*). As none of these studies included neutral trials, though, it is not possible to directly test this prediction at present. However, neutral trials were included by Stoffels and van der Molen (1988) in a hybrid flanker-auditory accessory Simon task, and here, the data do indeed suggest that the within-trial distractor interaction is primarily driven by delayed responses on flanker-incompatible location-congruent trials (at least when trial presentation was mixed rather than blocked; see their Figure 2). Using a hybrid flanker-letter Stroop task, Rey-Mermet and Gade (2016; Experiment 1c) also employed neutral trials, and found that responses were selectively delayed on flanker-compatible Stroop-incongruent trials. Applying the same logic as before, this could be interpreted as suggesting that in this experiment, the flanker information (i.e., whether or not the color of the central target letter matches the color of the flanking letters) was processed earlier than the Stroop information (i.e., whether the color of the central target letter matches the meaning of the word composed of target and flanking letters).

Obviously, these analyses are not meant to imply that the RAE can explain any and all hybrid interference-task results. For instance, although IOR-based tasks (Table 2, bottom) typically produce reduced interference effects at cued relative to uncued locations, this pattern might only bear a superficial similarity to the RAE. In fact, interpreting it in terms of inhibited processing at cued locations (rather than in terms of high-level confusion) seems to be more parsimonious as well as more intuitively plausible. It is also worth noting that combinations with a Stroop task often do not produce any within-trial interactions (see Table 1), possibly because of differences in the time course of interference effects (Hommel, 1997). The apparent discrepancy between this general trend and the Rey-Mermet and Gade (2016) results discussed above might be related to differences in the time course of word and color processing when both features form a coherent whole (as in standard Stroop tasks) compared with when they are separated by coloring different letters of the word differently (as in the Rey-Mermet & Gade, 2016, study). Future research, ideally using electrophysiological measures, will need to investigate this issue directly.

<sup>15</sup> Furthermore, note that CSEs might not result from a single mechanism, but rather, as Egner (2014) argues, from multiple, integrated processes, the exact combination depending on the physical and statistical properties of the task at hand. Within such a framework, the current result that older adults produce CSEs of the same magnitude and just as domain-specific as those of young adults would not be interpreted as favoring one account of CSEs over another, nor as favoring one account of cognitive aging over another. Instead, the present study would be seen as providing one set of specific task parameters under which CSEs are not influenced by old age. Future research will have to systematically vary task parameters in order to map out under which conditions aging effects do or do not occur.

Overall, however, it seems clear that for a substantial part of the literature, apparent domain-general within-trial interactions might instead result from confusion at subsequent (higher-level or meta-cognitive) processing levels. Such “awareness-induced slowing” is reminiscent of at least two other phenomena: posterror slowing and “analysis paralysis.” Posterror slowing refers to the finding that responses are often slower when they follow an error than when they follow a correct response (for a review, see Danielmeier & Ullsperger, 2011). Two aspects of posterror slowing are of particular interest in the present context. First, like the RAE, posterror slowing seems to require awareness of “something going wrong,” as it occurs only if the participant has noticed the error, whereas errors that have gone undetected do not produce any behavioral adaptations (e.g., Hoonakker, Doignon-Camus, & Bonnefond, 2016; Klein et al., 2007; Wessel, Danielmeier, & Ullsperger, 2011). Second, older adults tend to show larger posterror slowing than do young adults, without a concomitant increase in accuracy (Dutilh, Forstmann, Vandekerckhove, & Wagenmakers, 2013; Ruitenberg, Abrahamse, De Kleine, & Verwey, 2014).<sup>16</sup>

At an even broader level, the awareness-related slowing evident in both the RAE and posterror slowing is reminiscent of “analysis paralysis,” the break-down of decision-making processes through overthinking. In sports, this is known as “choking” (an expert athlete’s sudden failure to perform a highly trained skill when under pressure; Baumeister, 1984). A major contributing factor to choking is the conscious monitoring of sensorimotor processes, which is assumed to interfere with their normally smooth, automatic execution (for recent reviews, see Mesagno & Beckmann, 2017; Roberts, Jackson, & Grundy, 2019). The same phenomenon also occurs in everyday tasks, from the detrimental effect of an internal focus on motor skill learning (for reviews, see Kim, Jimenez-Diaz, & Chen, 2017; Wulf, 2013) to older adults’ increased but, importantly, nonfunctional use of attentional resources in maintaining postural and gait stability (see reviews by Li, Bherer, Mirelman, Maidan, & Hausdorff, 2018; Mak, Young, Chan, & Wong, 2020).

## Synopsis and Outlook

The present study has provided evidence that in sensorimotor control tasks, a self-contradictory sequence of events—requiring the reactivation of a recently discarded response alternative—slows response execution, provided these events are available to conscious awareness, an effect disproportionately enlarged in older adults. We have argued that this slowing does not reflect a direct inhibitory aftereffect (i.e., the response takes longer to reach execution threshold because it has been suppressed below baseline), but instead reflects a reluctance to reactivate the discarded response (akin to the aversion to repeat an erroneous response). Future studies using electrophysiological measures should investigate this issue directly.

As mentioned before, the RAE appears to share a general “avoid the discarded” feature with error aversion and numerous putative inhibitory aftereffects like the NCE, IOR, NP, N-2 repetition costs, and spontaneous alternation. It would be particularly interesting to explore whether there are common processing principles—or even a common mechanism—underlying such “been there, done that” phenomena (see Phillimore & Klein, 2019), for instance by using computational modeling to investigate underlying latent variables.

Several models already exist for standard interference tasks (specifically the Flanker task; see Evans & Servant, 2020), though to the best of our knowledge, no model has yet been developed to provide an account of performance in (two- or four-alternative) hybrid interference tasks. We hope that the data from the present study (<https://osf.io/2643d/>) will be useful to such future modeling developments.

<sup>16</sup> We were able to confirm the latter in the data from Experiment 3: Although, as noted above, the two age groups produced similar error rates, older adults showed significantly enlarged posterror slowing, even after accounting for overall RT differences (posterror to postcorrect RT ratio = 1.113 [ $SD = 0.11$ ] for older and 1.041 [ $SD = 0.76$ ] for young adults,  $t(31.03) = 2.31$ ,  $p = .028$ ). However, further analyses revealed that posterror slowing and the RAE were not correlated in either young or older adults (both  $r_s < 0.16$ , both  $p_s > .51$ ), suggesting that despite the conceptual similarities between the two measures, they do not reflect the same underlying mechanism. It would be interesting to investigate this issue more closely in a larger sample and with a task that simultaneously assesses error awareness.

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