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Modulations of Response Activation Contribute to Block-Wide Control: Evidence From Proportion Congruency Effects in the Prime-Probe Task

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Distractor-related congruency effects are smaller in blocks of mostly incongruent (vs. mostly congruent) trials. It remains unclear, though, how control processes produce this proportion congruency effect (PCE). The *attentional shift* account posits that experiencing conflict more frequently in mostly incongruent (vs. mostly congruent) blocks biases control processes to shift attention away from the distractor. The *response modulation* account posits that, if participants identify the distractor before the target, control processes use the distractor's identity to prepare a congruent response in mostly congruent blocks and/or an incongruent response in mostly incongruent blocks. We conducted four experiments ($N = 192$) to investigate whether a modulation of response activation contributes to the PCE in the prime-probe task. We observed a larger PCE when the prime/distractor appeared 166 ms before (vs. simultaneously with) the probe/target (Experiment 1) and a PCE without an overall congruency effect at a longer, 933-ms stimulus onset asynchrony (SOA; Experiment 2). Critically, the latter PCE was associated with a negative congruency effect in mostly incongruent blocks, consistent with a modulation of response activation but not a shift of attention. Finally, in a modified prime-probe task, wherein participants respond to each stimulus before the next one appears (1,133 ms SOA), we observed analogous PCEs and negative congruency effects (Experiment 3) and a PCE-like effect in response force just before the probe appeared (Experiment 4). These findings indicate an independent contribution of control processes that modulate response activation to the PCE at long prime-probe SOAs, which extends beyond minimizing distraction from irrelevant stimuli.

Keywords: conflict adaptation, proactive control, response force, proportion congruency effect

Coping with distraction is crucial to achieving behavioral goals. Consider, for example, asking a friend to name their favorite movie at a party. If another partygoer suddenly blurts out the name of a movie, your friend must cope with this distraction to answer the question correctly. To this end, your friend could focus on your lips or voice to make sure they understand the question and/or inhibit the natural tendency to repeat the answer given by the other partygoer. Coping in these ways could increase the probability of answering correctly, although the answer might still come more slowly and less accurately than if there had been less (or no) distraction.

In the laboratory, researchers employ so-called distractor-interference tasks to investigate how people cope with distraction from irrelevant stimuli (Eriksen & Eriksen, 1974; Simon, 1969; Stroop, 1935). In these tasks, participants identify a target while ignoring one or more distractors. In the prime-probe task, for example, participants identify a probe/target while ignoring a prime/distractor that appears earlier in time at the same location (Kunde & Wühr, 2006). In congruent trials, the distractor (e.g., an arrow pointing left) cues the same response as the target (e.g., another arrow pointing left). In incongruent trials, however, the distractor (e.g., an arrow pointing left) cues a different response than the target (e.g., an arrow pointing right). The typical outcome is that participants respond more slowly in incongruent relative to congruent trials. Researchers interpret this congruency effect as a measure of distractibility, as its presence indicates that participants cannot completely filter irrelevant stimuli (MacLeod, 1991).

Analogous to our example of answering a question at a party, the congruency effect varies in two ways that suggest the operation of cognitive control mechanisms for coping with distraction. First, the congruency effect is smaller after incongruent relative to congruent

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The preregistration, task scripts, data analysis scripts, and raw data are available on the Open Science Framework: Experiment 1 at https://osf.io/2ac8j/, Experiment 2 at https://osf.io/kbdjp/, Experiment 3 at https://osf.io/sdkyt/, and Experiment 4 at https://osf.io/5nw64/.

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trials (Gratton et al., 1992). This *congruency sequence effect* (CSE) suggests a control mechanism for coping with distraction at relatively short timescales (i.e., from one trial to the next). Second, the congruency effect is smaller in blocks of mostly incongruent trials than in blocks of mostly congruent trials (Logan & Zbrodoff, 1979). This *proportion congruency effect* (PCE) suggests a control mechanism for coping with distraction at relatively long timescales (i.e., block-wide control; for other PCEs that do not involve a contrast between two blocks, see Bugg & Crump, 2012).

Feature integration confounds related to stimulus and response repetitions in consecutive trials and contingency learning confounds related to pairing each distractor with the congruent response more or less often than with each possible incongruent response can produce CSEs and PCEs independent of control processes (Hommel et al., 2004; Mayr et al., 2003; Schmidt et al., 2007; Schmidt & Besner, 2008). Confound-minimized tasks that produce CSEs and PCEs without such confounds, however, are now readily available (Bugg & Chanani, 2011; Kim & Cho, 2014; Schmidt & Weissman, 2014; Spinelli & Lupker, 2023; Spinelli et al., 2019; Wühr et al., 2015). Therefore, researchers can employ such tasks to investigate the nature of "control-driven" CSEs and PCEs (see Braem et al., 2019, for a consensus article and review).

Cognitive Control Accounts of the PCE

There are two main cognitive control accounts of the PCE. First, there is the *congruency-triggered response modulation* account, hereafter called the *response modulation* account (Logan, 1985; Logan & Zbrodoff, 1979). Second, there is the *conflict-triggered attentional shift* account (Botvinick et al., 2001), hereafter called the *attentional shift* account. Note that neither account assumes the operation of explicit or intentional processes. Indeed, this assumption would likely be incorrect as PCE modulations are largely divorced from participants' awareness of the PCE manipulation (Blais et al., 2012). Note as well that the response modulation account was the initial explanation of the PCE (Logan, 1985; Logan & Zbrodoff, 1979), but the attentional shift account has become more popular in recent years (Bugg, 2014; Schmidt, 2013; Spinelli & Lupker, 2023). Still, as we describe below, virtually no studies have differentiated between these accounts using confound-minimized tasks. In particular, virtually no studies have shown that—in at least some situations—the PCE varies in ways that the response modulation account can explain but the attentional shift account cannot explain or vice versa. As the purpose of the present study is to begin to fill this gap in the literature, we describe each of these accounts next.

The *response modulation* account posits that control processes modulate response activation to produce the PCE but only if stimulus–response translation proceeds more quickly for the distractor than for the target. Under such conditions, proactive control processes should have time to modulate the activation of the response cued by the distractor in ways that facilitate making a congruent response to the target in mostly congruent blocks and/or an incongruent response to the target in mostly incongruent blocks (Logan, 1985; Logan & Zbrodoff, 1979). Control processes, for example, may enhance the response cued by the distractor in mostly congruent blocks but inhibit that response in mostly incongruent blocks. In this account, the perceived utility of the distractor for predicting the correct response to the target (high in mostly congruent blocks or low in mostly incongruent blocks) triggers control processes to modulate response activation related to the distractor response as described above. Put another way, control processes learn a global "rule"—the distractor predicts the congruent response in mostly congruent blocks or the incongruent response in mostly incongruent blocks—that applies to all stimuli and then modulate response activation accordingly. Preparing for a congruent response in mostly congruent blocks speeds performance in congruent trials but slows performance in incongruent trials, thereby increasing the congruency effect. Preparing for an incongruent response in mostly incongruent blocks, however, slows performance in congruent trials but speeds performance in incongruent trials, thereby reducing the congruency effect. Therefore, the congruency effect is smaller in mostly incongruent (vs. mostly congruent) blocks.

Note that Logan and colleagues proposed the response modulation account to explain the PCE in a spatial Stroop task wherein location words served as targets and spatial locations served as distractors. They assumed that, analogous to the Simon task (Hommel, 1993), stimulus–response translation is faster for the irrelevant spatial location than for the relevant word meaning even though both stimulus dimensions appear simultaneously. The response modulation account may also explain PCEs in tasks wherein a distractor appears before a target (e.g., Schmidt, 2017).

The *attentional shift* account posits that control processes shift attention away from the distractor and toward the target (Botvinick et al., 2001). Here, participants experience greater conflict between competing response alternatives in incongruent relative to congruent trials. That is, in incongruent trials, the competing responses that the distractor and the target activate conflict with each other. This conflict is typically indexed by longer response time (RT) in incongruent versus congruent trials (i.e., a congruency effect; Yeung et al., 2011). Critically, experiencing such conflict more often in mostly incongruent (vs. mostly congruent) blocks triggers proactive control processes to shift attention away from the distractor and toward the target more strongly in mostly incongruent blocks than in mostly congruent blocks. Put another way, experiencing conflict more often, or to a greater degree, leads to a larger attentional shift away from the distractor and toward the target. The result of this larger attentional shift is a smaller congruency effect in mostly incongruent (vs. mostly congruent) blocks (i.e., because, in mostly incongruent blocks, the distractor exerts a smaller influence on target processing).

How to Differentiate the Response Modulation and Attentional Shift Accounts

The response modulation and attentional shift accounts share a number of predictions related to the PCE (e.g., concerning the role of congruency between responses cued by the distractor and the target in inducing control). However, the two accounts differ with regard to at least three critical predictions due to the following difference. The attentional shift account posits that the PCE increases with the size of the overall congruency (i.e., conflict) effect (i.e., the average congruency effect across mostly congruent blocks and mostly incongruent blocks). In contrast, the response modulation account posits that the PCE increases when the distractor has a "head start" in stimulus–response translation over the target relative to when it does not, and that giving the distractor such a "head start" increases the size of the PCE independent of conflict. Keeping this important difference in mind, we will now describe the three critical predictions.

First, the two accounts differ with regard to whether the PCE should be larger when participants translate a distractor into a response before—relative to simultaneously with—a target. The response modulation account always predicts a larger PCE when a distractor has a "head start" in stimulus–response translation over a target because only then do control processes have time to modulate this response before participants execute the target response (Logan & Zbrodoff, 1979). In contrast, the attentional shift account predicts a larger PCE in the "head start" condition only when differences in conflict between incongruent and congruent trials—as indexed by the size of the overall congruency effect (Yeung et al., 2011)—are greater in the "head start" condition than in the "simultaneous" condition. The underlying logic here is simple: Because the attentional shift account posits that differences in conflict trigger the PCE, the size of the PCE should scale with the size of the overall congruency (i.e., conflict) effect.

Second, the response modulation and attentional shift accounts differ with regard to whether a PCE can appear in the complete absence of an overall congruency effect. The response modulation account makes this prediction because only the perceived utility of the distractor for predicting the response to the target triggers control (Logan, 1985; Logan & Zbrodoff, 1979). Therefore, experiencing conflict is not necessary for a PCE to appear. The attentional shift account, however, does not predict a PCE without an overall congruency effect. Here, heightened conflict in incongruent relative to congruent trials—as indexed by longer RT in incongruent relative to congruent trials (i.e., a congruency effect; Yeung et al., 2011)—is what triggers control processes to shift attention away from the distractor and toward the target. Thus, without an overall congruency (i.e., conflict) effect, there should be no PCE (Schmidt, 2017).

Third, the response modulation and attentional shift accounts differ with regard to whether a PCE can be associated with a negative (i.e., reverse) congruency effect in mostly incongruent blocks. The response modulation account predicts a negative congruency effect if control processes modulate response activation in ways that speed responses more in incongruent trials than in congruent trials (Logan & Zbrodoff, 1979). For example, as we described earlier, a negative congruency effect may arise in mostly incongruent blocks if control processes inhibit the response cued by the distractor before participants respond to the target, thereby selectively slowing responses in congruent trials. Of course, such a negative congruency effect is more likely to appear when the overall congruency effect is small or absent than when the overall congruency effect is large and positive as in most tasks. The reason is that control processes that modulate response activation need not overcome a large main effect of trial type to produce a negative congruency effect when the overall congruency effect is small or absent. In contrast, the attentional shift account does not predict a negative congruency effect. The logic here is that even shifting all of one's attention away from the distractor could eliminate the congruency effect (e.g., by preventing participants from processing the distractor), but not reverse it.

Note that the response modulation account's second prediction that a PCE can appear in the absence of an overall congruency effect is clearly related to—but not simply a special case of—its third prediction that a PCE can be associated with a negative congruency effect in mostly incongruent blocks. A PCE may appear without an overall congruency effect, for example, if there is a nonsignificant positive congruency effect in mostly congruent blocks whose size matches that of a nonsignificant negative congruency effect in mostly incongruent blocks. In other words, the absence of an overall congruency effect may not always be associated with a significant negative congruency effect in mostly incongruent blocks. Further illustrating that the response modulation account's second and third predictions are at least somewhat independent, a negative congruency effect might appear when there is a small overall congruency effect if a task produces a significant positive congruency effect in mostly congruent blocks that is larger than the significant negative congruency effect that appears in mostly incongruent blocks.

Prior Findings Differentiating Between the Response Modulation and Attentional Shift Accounts

To our knowledge, virtually no studies have differentiated between the response modulation and attentional shift accounts of the PCE using confound-minimized protocols. That is, almost no studies have shown that—in at least some situations—the PCE varies in ways that one type of control process (e.g., a modulation of response activation) can explain but the other type of control process (e.g., an attentional shift) cannot explain. A notable exception, however, comes from an electroencephalography study of the prime-probe task (Wendt et al., 2014). The authors measured the N1 event-related potential component whose amplitude increases with the amount of attention that a participant allocates to perceptual aspects of a stimulus. They reported that N1 amplitude time-locked to the prime/distractor was smaller in mostly incongruent (vs. mostly congruent) blocks. Critically, this effect generalized to neutral primes (i.e., primes that were neither congruent nor incongruent with their associated probes and that were presented in a fixed proportion across blocks), which is important because the other primes were associated with contingency learning confounds. Consequently, the authors attributed this effect to a shift of attention away from the distractor and toward the target (see also, Wendt et al., 2012). They acknowledged, however, that expectations about the upcoming target's perceptual features might have triggered this shift of attention, rather than heightened conflict. They also acknowledged that the attentional shift that they observed does not rule out an additional contribution of postperceptual processes to the PCE.

Consistent with the latter possibility, data indicating that PCEs are sometimes associated with negative congruency effects in mostly incongruent blocks (Hommel, 1994; Logan & Zbrodoff, 1979; Luo et al., 2023; Marble & Proctor, 2000; Ridderinkhof, 2002; Stürmer et al., 2002; Toth et al., 1995) appear consistent with the response modulation account but not with the attentional shift account. It is difficult to draw firm conclusions based on such findings, however, because contingency learning confounds were present in all of these studies and, therefore, could have produced the corresponding PCEs and negative congruency effects independently of cognitive control processes (Luo et al., 2023; Schmidt, 2013; Schmidt & Besner, 2008).

While data from PCE studies are to this point ambiguous, we note that three findings from the confound-minimized prime-probe task appear more consistent with the response modulation account of the *CSE* than with the attentional shift account. First, the CSE is larger when the prime/distractor appears 166 ms before—versus simultaneously with—the probe/target, regardless of whether the overall congruency effect is larger at the 166-ms stimulus onset asynchrony (SOA) or at the 0-ms SOA (Weissman et al., 2015, Experiments 1 and 2). Second, when a relatively long (e.g., 1,133 ms) SOA separates the initial prime from the subsequent probe, a CSE appears without an overall congruency effect (Weissman et al., 2015, Experiment 3). Third, the CSE at long SOAs is associated with a negative congruency effect after incongruent trials (Weissman et al., 2015, Experiment 3). These findings suggest the possibility that a modulation of response activation also contributes to other indices of cognitive control in the prime-probe task such as the PCE. Such a finding would serve to integrate the literatures on the CSE and PCE (literatures that, with some exceptions such as Torres-Quesada et al., 2013, 2014, have been largely separate) by indicating that somewhat similar control processes operate at short and long timescales in the prime-probe task.

Response Modulation Is Not Specific to Minimizing Distraction

Recent findings suggest that the response modulation mechanism underlying the CSE makes a broader contribution to cognition than minimizing distraction from irrelevant stimuli. First, consider tasks wherein the SOA separating the prime and the probe is relatively long (e.g., 1,133 ms) and participants respond to both (a) the prime as soon as it appears and (b) the probe as soon as it appears (with the prime and probe still forming a single trial). In such tasks, there is still a robust CSE in mean probe RT. That is, mean probe RT is still affected by the interaction between the congruency of the prime and the probe in the current trial and the congruency of the prime and the probe in the previous trial (Grant & Weissman, 2019, 2023; Weissman, 2019; Weissman et al., 2017, 2020). This outcome shows that a CSE appears in mean probe RT even in the absence of task-irrelevant stimuli. Second, as in the standard prime-probe task, the CSE in this "modified" prime-probe task often appears in the complete absence of an overall congruency effect and with a negative congruency effect after incongruent trials (e.g., Weissman, 2019). Third, just before the probe appears in the modified prime-probe task, participants exert greater finger pressure on the key corresponding to (a) the congruent (vs. incongruent) response after a congruent trial and (b) the incongruent (vs. congruent) response after an incongruent trial (Weissman, 2019). This result provides direct support for the response modulation account.

More broadly, the findings above suggest that the response modulation mechanism underlying the CSE is not specific to minimizing distraction from irrelevant stimuli. Rather, they suggest that this mechanism modulates response activation to prepare for an upcoming stimulus (e.g., a probe) that has the same relationship (e.g., congruent or incongruent) to a preceding stimulus (e.g., a prime) as in the previous trial regardless of whether the preceding stimulus is a distractor or a target. This outcome may indicate a broader role for this mechanism in learning abstract relationships between stimuli and/or responses (e.g., similar vs. dissimilar; Weissman et al., 2020). Most important, observing a PCE not only in the standard prime-probe task but also in the modified prime-probe task would provide converging evidence that overlapping response modulation control mechanisms contribute to the PCE and the CSE in these tasks.

The Present Study

The overall goal of the present study was to investigate whether a modulation of response activation contributes to the "control-driven" (i.e., confound-minimized) PCE. We did so by determining whether—in some situations—the PCE varies in ways that the response modulation account can explain but the attentional shift account cannot explain. We reasoned that such an outcome would provide novel support for the response modulation account without ruling out the possibility that an attentional shift also contributes to the PCE in some situations.

Our approach was to determine whether prior findings supporting the response modulation account of the "control-driven" CSE, which we reviewed earlier, generalize to the "control-driven" PCE. In Experiment 1, we investigated whether the PCE is larger when a 166-ms (vs. 0 ms) SOA separates the initial prime/distractor from the subsequent probe/target. In Experiment 2, we employed a 933-ms prime-probe SOA to investigate whether a PCE appears even in the complete absence of an overall congruency (i.e., conflict) effect. In Experiment 3, we investigated whether—analogous to the CSE—the PCE is larger in the modified prime-probe task, wherein participants respond to both the prime and the probe, than in the standard prime-probe task, wherein participants respond only to the probe. In Experiment 4, we employed force-sensitive keyboards to investigate whether a PCE-like effect appears in subthreshold response force just before probe onset in the modified prime-probe task.

To implement this approach, we used a confound-minimized protocol that separates control processes from confounds by including a mixture of "inducer" and "diagnostic" items (Spinelli & Lupker, 2023). For the inducer items, both (a) the relative proportions of congruent and incongruent trials and (b) the nature of contingency learning confounds (i.e., whether the prime is associated more often with the congruent response or the incongruent response) differ between mostly congruent and mostly incongruent blocks. It is difficult, therefore, to attribute a PCE for the inducer items specifically to control processes (Schmidt & De Houwer, 2011). For the diagnostic items, however, the relative proportions of congruent and incongruent trials (50–50) remain constant across all blocks, and there are no contingency learning confounds. Therefore, a PCE for the diagnostic items likely indexes an effect of manipulating the relative proportions of congruent and incongruent inducer items on control processes that influence the size of the congruency effect. For this reason, the diagnostic items are the most relevant items for evaluating the predictions of the response modulation and attentional shift accounts.

Experiment 1

In Experiment 1, we compared the PCE in blocks wherein the prime appears 166 ms before the probe to the PCE in blocks wherein the prime and probe appear simultaneously. If a modulation of response activation related to the prime (e.g., greater inhibition of the prime response in mostly incongruent blocks than in mostly congruent blocks) contributes to the PCE in the prime-probe task, then the PCE should be larger at the 166-ms SOA than at the 0-ms SOA. Indeed, control processes should have more time to modulate response activation related to a distractor if the distractor has a "head start" in stimulus–response translation relative to the target (Burle et al., 2005; Logan & Zbrodoff, 1979; Ridderinkhof, 2002; Weissman et al., 2015). Alternatively, if the PCE in the prime-probe task is produced only by a shift of attention toward the probe (e.g., greater attention in mostly incongruent blocks than in mostly congruent blocks), then the PCE should not differ between the 166- and 0-ms SOAs provided that the overall congruency (i.e., conflict) effect is similar at these two SOAs. For example, since the probe is always smaller than the prime, control processes could shift attention to stimuli matching the probe's size in mostly incongruent blocks at both SOAs, leading to similar PCEs (Weissman et al., 2015). If the overall congruency effect differs at the two SOAs, then the PCE should be larger at whichever SOA is associated with the larger (vs. smaller) overall congruency effect.

Method

Participants

We chose to collect usable data from 48 subjects for four reasons. First, Spinelli and Lupker (2023, Experiment 3) observed a robust PCE with 48 subjects. Second, the PCE in mean RT for their critical diagnostic items was associated with a partial η^2 value of 0.361, which requires 26 subjects to achieve 95% power at an α of .05 according to G*Power 3.1.9.7 (Faul et al., 2007). Third, in a corresponding study of the CSE (Weissman et al., 2015, Experiment 1), the partial eta squared values associated with (a) the CSE at the 166-ms SOA (0.79) and (b) the larger CSE at the 166-ms (vs. 0 ms) SOA (0.76) were nearly identical. This was because—in line with the response modulation account—there was no CSE at the 0-ms SOA. We therefore reasoned that even if the effect size for the PCE at the 166-ms SOA was the same as that for the diagnostic items from Experiment 3 of Spinelli and Lupker (2023; i.e., 0.361), 26 subjects would provide 95% power to observe a larger PCE at the 166-ms SOA (vs. 0 ms) SOA. Fourth, a recent study observed a small PCE (partial η^2: 0.17) in a task wherein the distractor and the target were likely translated into responses at about the same time (Davis et al., 2020), which could be the case for the present 0-ms SOA. Thus, to provide at least 86% power for observing a PCE in these blocks, we decided to collect usable data from 48 participants.[1]

Forty-nine students from the University of Michigan's Psychology Subject Pool participated for course credit. We excluded the data from one participant who performed with less than 75% overall accuracy. Thus, the final data analyses included data from 48 participants (17 male, 31 female; mean age, 19.2 years; age range: 18–25 years).[2] The University of Michigan's Health Sciences and Behavioral Sciences Institutional Review Board deemed all the experiments that we report in this article to be exempt from oversight.

Stimuli and Apparatus

We employed four large arrows and four small arrows as stimuli. The large arrows pointed left, right, up, and down (approximate sizes in degrees of visual angle, left and right: 8.0° × 4.5°; up and down: 4.5° × 8.0°). The small arrows also pointed left, right, up, and down (left and right: 2.5° × 1.7°; up and down: 1.7° × 2.5°). All arrows were hollow, which allowed us to present small arrows embedded within large ones in some of the blocks, as explained below. We ran the experiment using PsychoPy Version 2022.2.4 (Peirce et al., 2019) on a Windows 10 PC.

Task

At the beginning of each block—and only then—there was a fixation cross for 1.8 s. A 0.2-s blank screen followed the cross. Next, the trials appeared (Figure 1). In 0-ms SOA blocks, the prime (a large hollow arrow) and the probe (a small hollow arrow) appeared at the same time (duration, 100 ms) with the small probe arrow embedded within the large prime arrow. In 166-ms SOA blocks, the prime (100 ms) and a blank screen (66 ms) preceded the probe (100 ms).[3] Participants had a maximum of 2.5 s from prime onset to respond, but responses to the probe that occurred 900 ms or more after probe onset were counted as "Too Slow" (see below). Following a response, or 2.5 s after prime onset if there was no response, there was a 1,000-ms response-to-stimulus interval (RSI). All stimuli appeared in white on a black background.

We instructed participants to press a key on a QWERTY keyboard to indicate the direction in which the small arrow pointed. They were told to press "f" (left middle finger), "g" (left index finger), "j" (right middle finger), or "n" (right index finger) to indicate that the small probe arrow pointed "left," "right," "up," or "down," respectively. If participants responded correctly within the 900-ms response deadline, a blank screen appeared during the 1,000-ms RSI. If participants responded before the probe arrow appeared, pressed the wrong key within 900 ms of the probe arrow's appearance, or did not respond at all within 2.5 s of prime arrow onset, the word "Error" appeared during the RSI. If participants responded after the 900-ms response deadline but still within 2.5 s of prime arrow onset, the words "Too Slow" appeared during the RSI (regardless of whether their response was correct or incorrect). We provided immediate feedback to encourage participants to respond within 900 ms and/or correctly in subsequent trials.

Experimental Design

We used a within-participants design with four factors: (1) prime-probe SOA (0 ms, 166 ms), (2) block type (mostly congruent, mostly incongruent), (3) item type (inducer, diagnostic), and (4) trial type (congruent, incongruent). All trials from a given prime-probe SOA (e.g., 0 ms) appeared in the first or second half of the experiment.

Each prime-probe SOA (i.e., 0 and 166 ms) began with a single "unbiased" block of 32 practice trials, wherein congruent and incongruent trials appeared equally often. The purpose of the practice block was to familiarize subjects with a given prime-probe SOA. Next, we presented each of the two possible combinations of that prime-probe SOA and block type (e.g., 166 ms—mostly congruent and 166 ms—mostly incongruent). Each combination began with a single, 64-trial "adjustment" block. The purpose of this adjustment block was to familiarize subjects with the relative proportions of congruent and incongruent trials in the current block type. Three 64-trial test blocks followed the adjustment block. We counterbalanced the order in which the four possible combinations of prime-probe SOA and block type appeared across participants with the constraint, noted above, that all trials from the same prime-probe SOA appeared in either the first or the second half of the

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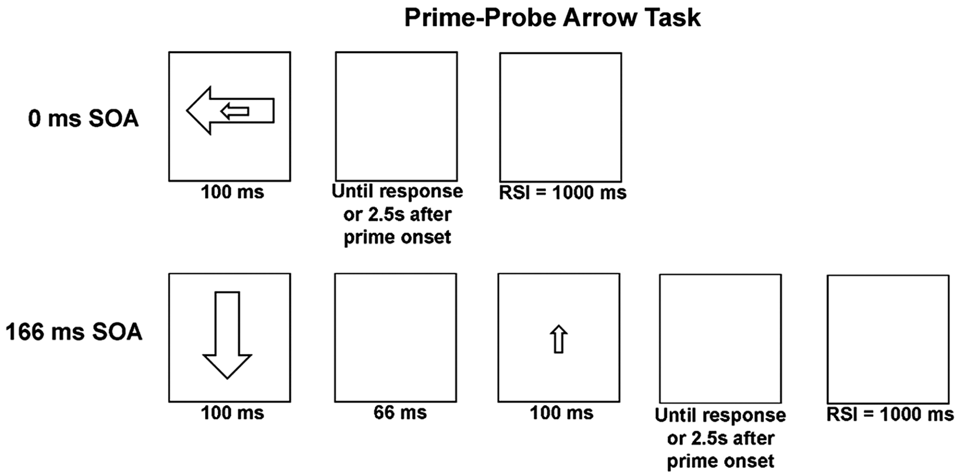
[1] We sought to achieve at least 80% power ($\alpha = .05$) for observing the effects of interest in our experiments.

[2] In our preregistration, we indicated that we would exclude participants who self-reported a history of seizures, concussions, neuropsychiatric diseases or disorders, and head trauma. Due to an oversight on our part, however, we did not present these questions to participants. All participants did, however, self-report normal or corrected-to-normal (e.g., with glasses) vision and hearing.

[3] In our preregistration, we indicated that each stimulus would appear for 133 ms. Due to a programming error, however, each stimulus appeared for only 100 ms.

Figure 1

The Prime-Probe Arrow Task in Experiment 1



Note. At the 0-ms SOA (top), the prime and probe arrows appeared simultaneously. At the 166-ms SOA (bottom), the prime arrow appeared before the probe arrow. At each SOA, we instructed participants to press one of four keys to indicate the direction in which the second (i.e., probe) arrow points. The time beneath each box indicates the duration of the corresponding trial component. SOA = stimulus onset asynchrony; RSI = response-to-stimulus interval.

experiment. Within each block, inducer and diagnostic stimuli appeared in a random order.

Across the 192 test trials in each of the four combinations above, the frequencies of congruent and incongruent inducer and diagnostic stimuli matched the frequencies of the corresponding trial types in Tables 7 (for the mostly congruent blocks) and 8 (for the mostly incongruent blocks) from Spinelli and Lupker (2023, Experiment 3). Since there were 192 trials per block in their study but only 64 in ours, we divided each of the frequencies in their Tables 7 and 8 by three in each 64-trial block (see Tables 1 and 2). As in their study, the absolute value of the correlation between prime and probe values, as measured by the "contingency coefficient" (Melara & Algom, 2003), equaled 0.78 in (a) mostly congruent blocks and (b) mostly incongruent blocks. Also as in Spinelli and Lupker's (2023) study, two nonoverlapping sets of stimuli (i.e., a left/right set and an up/down set) were used as inducer stimuli (i.e., the left–right set) and diagnostic stimuli (i.e., the up–down set). Finally, although Spinelli and Lupker (2023) included two versions of their task, each with a different set of four colors and four color names, we included only a single version of our task with four prime arrows and four probe arrows.

Table 1

The Prime-Probe Combinations in a Mostly Congruent Block

		Prime			
		Inducer		Diagnostic	
Item type	Probe	Left	Right	Up	Down
Inducer	Left	14	2		
	Right	2	14		
Diagnostic	Up			8	8
	Down			8	8

Tables 1 and 2 also convey other important information. First, there were four possible congruent trials (i.e., trials in which the two arrows point in the same direction: left–left, right–right, up–up, and down–down) and four possible incongruent trials (i.e., trials in which the two arrows point in different directions: left–right, right–left, down–up, and up–down). Second, left and right prime and probe arrows served as inducer stimuli while up and down prime and probe arrows served as diagnostic stimuli. Third, inducer and diagnostic stimuli appeared equally often in each block. Fourth, we manipulated the proportion congruency of each block (mostly congruent or mostly incongruent) by varying the proportions of congruent and incongruent inducer stimuli while holding constant the proportions of congruent and incongruent diagnostic stimuli. In mostly congruent blocks, the inducer stimuli were congruent 87.5% of the time and incongruent 12.5% of the time. In mostly incongruent blocks, we reversed these proportions.

Given these designs, participants could learn contingencies between the prime arrows and the upcoming probe responses only for the inducer stimuli. That is, for the inducer stimuli, they could learn which probe response was most likely after each inducer prime arrow. In contrast, participants could not learn which probe response was most likely after each diagnostic prime arrow because the diagnostic stimuli were 50% congruent and 50% incongruent. Consequently, each diagnostic prime arrow was followed equally often by each diagnostic probe response.

Procedure

After reading a consent form on the computer screen, participants pressed one key to provide consent or another key to abort the experiment. No participant chose to abort the experiment. Each participant's pupils were positioned approximately 55 cm from the computer screen (enforced with a chin rest). The research assistant

Table 2
The Prime-Probe Combinations in a Mostly Incongruent Block

		Prime			
		Inducer		Diagnostic	
Item type	Probe	Left	Right	Up	Down
Inducer	Left	2	14		
	Right	14	2		
Diagnostic	Up			8	8
	Down			8	8

also explained the task (described earlier) and asked the participant to respond to the probe in each trial as quickly as possible without making mistakes. The research assistant also indicated the 900-ms response deadline.

Data Analyses

We analyzed the data in Jeffrey's Amazing Statistics Program version 0.18.0.0 (Jeffrey's Amazing Statistics Program Team, 2023) using repeated-measures analysis of variance (ANOVA). Separate ANOVAs were conducted for inducer and diagnostic items, as is typical for inducer–diagnostic designs (Bugg, 2014; Spinelli & Lupker, 2023). Further, for each of these item types, we analyzed mean probe RT (measured from probe onset) and mean probe error rate (ER) separately. We specified three within-participants factors in each ANOVA: (1) prime-probe SOA (0 ms, 166 ms), (2) block type (mostly congruent, mostly incongruent), and (3) trial type (congruent, incongruent).

In non-pre-registered analyses, we computed Bayes factors to assess the evidence for or against each effect of interest (e.g., each main effect or interaction). This involved conducting Bayesian, repeated-measures ANOVAs with the same factors as in the frequentist ANOVAs and comparing all models including an effect of interest to all models that were equivalent with the exception that they lacked that effect (i.e., by selecting "across matched models" in Jeffrey's Amazing Statistics Program; Keysers et al., 2020). Each comparison yielded a Bayes Inclusion Factor ($\mathrm{BF_I}$), which one may interpret as providing evidence for the alternative hypothesis (the effect of interest is present) or the null hypothesis (the effect of interest is absent). For example, a $\mathrm{BF_I}$ value of 5.2 indicates that the data are 5.2 times *more* likely under the alternative (vs. null) hypothesis while a $\mathrm{BF_I}$ value of 0.1 indicates that the data are 10 times *less* likely under the alternative (vs. null) hypothesis.

We excluded certain trials from these analyses on a subject-by-subject basis. In the analysis of mean RT, we excluded (a) trials with incorrect or omitted responses (5.6%), (b) trials following trials with incorrect or omitted responses, and (c) outliers (3.5%). We defined outliers as trials with probe RTs greater than 3 × Sn (Rousseeuw & Croux, 1993), calculated separately for each of the 16 conditions in our 2 × 2 × 2 × 2 experimental design. Sn is a robust estimator of scale that assumes neither a measure of central tendency nor a normal distribution. The lack of the latter assumption makes Sn appropriate for analyzing RT distributions (P. R. Jones, 2019), which are typically not normally distributed. We also excluded practice trials and trials in "adjustment" blocks. In the analysis of mean probe ER, we excluded the same trial types except for trials with incorrect responses because this criterion was the dependent measure in our analyses of mean ER.[4] Table 3 presents the conditional mean RTs and mean ERs in Experiment 1.

Transparency and Openness

We report our rationale for sample sizes, manipulations, dependent measures, and data exclusions. We also follow Journal Article Reporting Standards (Kazak, 2018). The preregistration, task scripts, data analysis scripts, and raw data are available on the Open Science Framework (OSF; https://osf.io/2ac8j/).

Results

Inducer Items

Mean RT. A single main effect was significant. In particular, there was a main effect of trial type, $F(1, 47) = 367.33$, $p < .001$, $\eta_p^2 = 0.89$, $\mathrm{BF_I} = 5.857 \times 10^{20}$. Mean RT was longer in incongruent trials (508 ms) than in congruent trials (438 ms).

All of the two-way interactions were significant. First, there was an interaction between proportion congruency and SOA, $F(1, 47) = 7.98$, $p = .007$, $\eta_p^2 = 0.15$, $\mathrm{BF_I} = 2.55$, because mean RT was longer in mostly incongruent versus mostly congruent blocks at the 166-ms SOA (475 ms vs. 465 ms) but numerically shorter in mostly incongruent versus mostly congruent blocks at the 0-ms SOA (475 ms vs. 478 ms). Second, there was an interaction between proportion congruency and trial type, $F(1, 47) = 224.83$, $p < .001$, $\eta_p^2 = 0.83$, $\mathrm{BF_I} = 1.841 \times 10^{14}$, indicating a PCE. Specifically, the congruency effect was 59 ms larger in mostly congruent blocks (100 ms) versus mostly incongruent blocks (41 ms). Third, there was an interaction between SOA and trial type, $F(1, 47) = 63.10$, $p < .001$, $\eta_p^2 = 0.83$, $\mathrm{BF_I} = 3.036 \times 10^7$: The congruency effect was larger at the 166-ms SOA (94 ms) than at the 0-ms SOA (47 ms).

Finally, the three-way interaction was significant, $F(1, 47) = 67.93$, $p < .001$, $\eta_p^2 = 0.59$, $\mathrm{BF_I} = 3.545 \times 10^{12}$ (Figure 2, top). The PCE was larger at the 166-ms SOA, 91 ms; $F(1, 47) = 228.91$, $p < .001$, $\eta_p^2 = 0.83$, $\mathrm{BF_I} = 3.634 \times 10^{21}$; Figure 2, top left, than at the 0-ms SOA, 25 ms; $F(1, 47) = 26.82$, $p < .001$, $\eta_p^2 = 0.36$, $\mathrm{BF_I} = 160808.92$; Figure 2, top right. No other effects were significant (all ps > .16).

Mean ER. All of the main effects were significant. First, there was a main effect of proportion congruency, $F(1, 47) = 12.51$, $p < .001$, $\eta_p^2 = 0.21$, $\mathrm{BF_I} = 10.54$: Mean ER was higher in mostly congruent blocks (7.0%) than in mostly incongruent blocks (4.3%). Second, there was a main effect of SOA, $F(1, 47) = 4.62$, $p = .037$, $\eta_p^2 = 0.24$, $\mathrm{BF_I} = 1.02$: Mean ER was higher at the 166-ms SOA (6.7%) than at the 0-ms SOA (4.7%). Third, there was a main effect of trial type, $F(1, 47) = 14.71$, $p < .001$, $\eta_p^2 = 0.24$, $\mathrm{BF_I} = 68.25$: Mean ER was higher in incongruent trials (7.7%) than in congruent trials (3.6%).

All of the two-way interactions were significant. First, there was an interaction between proportion congruency and SOA, $F(1, 47) = 21.07$, $p < .001$, $\eta_p^2 = 0.31$, $\mathrm{BF_I} = 171.01$: Mean ER was lower in mostly incongruent versus mostly congruent blocks at the 166-ms SOA (3.8% vs. 9.5%) but higher in mostly incongruent versus mostly congruent blocks at the 0-ms SOA (4.9% vs. 4.5%). Note that in the analysis of

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[4] We identified outliers using only correct RTs in the analysis of mean RT but using both correct *and* error RTs in the analysis of mean ER. Therefore, these two analyses yielded slightly different percentages of outliers.

Table 3
Mean Reaction Times and Mean Error Rates (and Corresponding Standard Errors) in Experiment 1

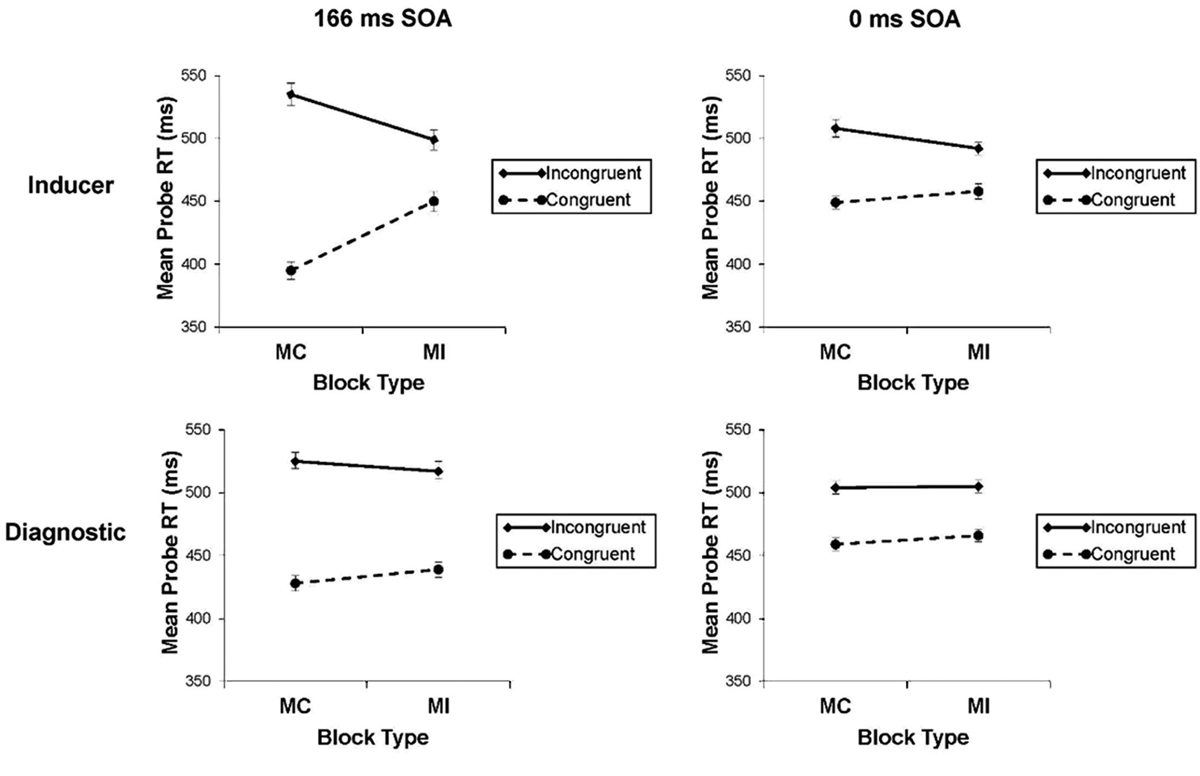
		Reaction time				Error rate			
SOA		166 ms		0 ms		166 ms		0 ms	
Item type	Trial type	MC	MI	MC	MI	MC	MI	MC	MI
Inducer	Congruent	395 (7)	450 (7)	449 (5)	458 (6)	1.4 (0.3)	3.7 (0.8)	3.5 (0.5)	6.0 (1.2)
	Incongruent	535 (9)	499 (8)	508 (7)	492 (6)	17.7 (2.8)	3.9 (0.1)	5.5 (1.0)	3.8 (0.5)
	Cong effect	140	49	59	34	16.3	0.2	2	−2.2
Diagnostic	Congruent	428 (6)	439 (6)	459 (5)	466 (5)	2.7 (0.5)	1.5 (0.3)	2.5 (0.3)	2.5 (0.4)
	Incongruent	525 (7)	517 (8)	504 (6)	505 (5)	8.6 (1.7)	6.1 (1.4)	4.3 (0.6)	3.4 (0.6)
	Cong effect	97	78	45	39	5.9	4.6	1.8	0.9

Note. Each parenthetical value indicates the standard error of the condition mean across participants. SOA = stimulus onset asynchrony; MC = mostly congruent blocks; MI = mostly incongruent blocks; Cong effect = congruency effect.

mean RT for inducer items, we observed the opposite pattern. That is, we observed slower responses in mostly incongruent versus mostly congruent blocks at the 166-ms SOA and slightly faster responses in mostly incongruent versus mostly congruent blocks at the 0-ms SOA. These contrasting patterns may reflect a speed–accuracy trade-off, particularly at the 166-ms SOA. Second, there was an interaction between proportion congruency and trial type, $F(1, 47) = 49.29$, $p < .001$, $\eta_p^2 = 0.51$, $\mathrm{BF_I} = 660674.62$, indicating a PCE: The congruency effect was larger in mostly congruent blocks (9.1%) than in mostly incongruent blocks (−0.9%), a difference of 10%. Third, there was an interaction between SOA and trial type, $F(1, 47) = 25.55$, $p < .001$, $\eta_p^2 = 0.35$, $\mathrm{BF_I} = 2601.08$: The congruency effect was larger at the 166-ms SOA (8.3%) than at the 0-ms SOA (−0.1% ms).

Finally, the three-way interaction was significant, $F(1, 47) = 15.57$, $p < .001$, $\eta_p^2 = 0.25$, $\mathrm{BF_I} = 7681.72$. The PCE was larger at the 166-ms SOA, 16.1%; $F(1, 47) = 39.20$, $p < .001$, $\eta_p^2 = 0.46$, $\mathrm{BF_I} = 3.807 \times 10^7$, than at the 0-ms SOA, 4.2%; $F(1, 47) = 8.17$, $p = .006$, $\eta_p^2 = 0.15$, $\mathrm{BF_I} = 20.07$. No other effects were significant (all ps > .15).

Figure 2
Proportion Congruency Effects in Experiment 1



Note. Mean RT as a function of trial type (congruent, incongruent) and block type (MC = mostly congruent, MI = mostly incongruent) plotted separately for each of the four combinations of SOA (166 ms, 0 ms) and item type (inducer, diagnostic). Positive and negative error bars indicate one standard error of the conditional mean across participants. SOA = stimulus onset asynchrony; RT = response time.

Diagnostic Items

Mean RT. A single main effect was significant. In particular, there was a main effect of trial type, $F(1, 47) = 397.25$, $p < .001$, $\eta_p^2 = 0.89$, $\mathrm{BF_I} = 3.996 \times 10^{21}$. Mean RT was longer in incongruent trials (513 ms) than in congruent trials (448 ms).

A pair of two-way interactions was significant. First, there was an interaction between proportion congruency and trial type, $F(1, 47) = 15.75$, $p < .001$, $\eta_p^2 = 0.25$, $\mathrm{BF_I} = 46.40$, indicating a PCE. Specifically, the congruency effect was 13 ms larger in mostly congruent blocks (71 ms) than in mostly incongruent blocks (58 ms). Second, there was an interaction between SOA and trial type, $F(1, 47) = 58.44$, $p < .001$, $\eta_p^2 = 0.55$, $\mathrm{BF_I} = 1.138 \times 10^7$: The congruency effect was larger at the 166-ms SOA (87 ms) than at the 0-ms SOA (41 ms).

Finally, the three-way interaction was significant, $F(1, 47) = 6.64$, $p = .013$, $\eta_p^2 = 0.12$, $\mathrm{BF_I} = 4.405$ (Figure 2, bottom). The PCE was larger at the 166-ms SOA, 19 ms; $F(1, 47) = 14.97$, $p < .001$, $\eta_p^2 = 0.24$, $\mathrm{BF_I} = 72.20$; Figure 2, bottom left, than at the 0-ms SOA, 6 ms; $F(1, 47) = 3.05$, $p = .087$, $\eta_p^2 = 0.06$, $\mathrm{BF_I} = 0.73$; Figure 2, bottom right. No other effects were significant (all *p*s > .15).

Mean ER. All of the main effects were significant. First, there was a main effect of proportion congruency, $F(1, 47) = 6.60$, $p = .013$, $\eta_p^2 = 0.12$, $\mathrm{BF_I} = 1.77$: Mean ER was higher in mostly congruent blocks (4.6%) than in mostly incongruent blocks (3.4%). Second, there was a main effect of SOA, $F(1, 47) = 6.35$, $p = .015$, $\eta_p^2 = 0.12$, $\mathrm{BF_I} = 2.72$: Mean ER was higher at the 166-ms SOA (4.7%) than at the 0-ms SOA (3.2%). Third, there was a main effect of trial type, $F(1, 47) = 18.96$, $p < .001$, $\eta_p^2 = 0.29$, $\mathrm{BF_I} = 292.44$: Mean ER was higher in incongruent trials (5.6%) than in congruent trials (2.3%).

A single two-way interaction was significant. Specifically, there was an interaction between SOA and trial type, $F(1, 47) = 9.66$, $p = .003$, $\eta_p^2 = 0.17$, $\mathrm{BF_I} = 13.34$, because the congruency effect was larger at the 166-ms SOA (5.3%) than at the 0-ms SOA (1.4%). No other effects were significant (all *p*s > .15).

Discussion

We observed a larger PCE at the 166-ms SOA than at the 0-ms SOA for inducer items and, most importantly, for diagnostic items. In fact, we did not even observe a significant PCE at the 0-ms SOA for diagnostic items. These findings are consistent with the response modulation account. According to this account, modulations of response activation after prime (i.e., distractor) onset take time to build up and, therefore, exert a greater influence on performance when the prime is translated into a response before the target (Ridderinkhof, 2002).

The attentional shift account, however, might also be able to explain these findings. First, the larger PCE at the 166-ms (vs. 0 ms) SOA could index control processes that shift attention to the target's smaller size *and* later temporal onset, not just toward the target's smaller size (Dignath et al., 2021). Although tasks without this confound still yield support for the response modulation account of the CSE (Dignath et al., 2021), this is not necessarily the case for the PCE. Second, the larger PCE at the 166-ms (vs. 0 ms) SOA may have occurred because the overall congruency effect was larger at the 166-ms SOA, resulting in greater conflict-triggered control (Botvinick et al., 2001; Yeung et al., 2011). Relatedly, the relatively small (nonsignificant) 6-ms PCE at the 0-ms SOA may have occurred because the 41-ms congruency (i.e., conflict) effect at this SOA was not large enough to trigger an attentional shift toward the target. Thus, it remains unclear whether a modulation of response activation contributes to the PCE.

Experiment 2

In Experiment 2, we sought once again to determine whether a modulation of response activation contributes to the PCE. To this end, we conducted a new study involving the 166-ms SOA from Experiment 1 and a longer 933-ms SOA. Based on previous results (Machado et al., 2007; Weissman et al., 2015), we expected to observe a small or absent overall congruency effect at the 933 ms SOA, because minimizing the temporal overlap of distractor and target response activations reduces the overall congruency effect (Hommel, 1993).

Assuming that the size of the overall congruency effect increases with differences in conflict between congruent and incongruent trials (Yeung et al., 2011), the attentional shift account makes two predictions. First, it predicts a larger PCE when the overall congruency effect is relatively large at the 166-ms SOA as compared to relatively small or absent at the 933-ms SOA. Second, it predicts either a small PCE or no PCE at the 933-ms SOA depending on whether the overall congruency effect is small or absent, respectively.

The response modulation account, however, does not predict a strong relationship between the size of the PCE and the size of the overall congruency effect when the prime appears before the probe (although the PCE would likely become smaller and vanish at extremely long prime-probe intervals). The underlying logic here is that as long as the prime appears before the probe, control processes should have time to modulate response activation related to the prime before the target appears (Weissman et al., 2015). Consequently, the response modulation account predicts a PCE whether or not the overall congruency effect is present or absent. Finally, when the overall congruency effect is small or absent, the response modulation account predicts a positive congruency effect in mostly congruent blocks and a *negative* (i.e., reverse) congruency effect in mostly incongruent blocks (Logan & Zbrodoff, 1979). In contrast, the attentional shift account does not predict a negative congruency effect. Even shifting all of one's attention away from the distractor could eliminate the congruency effect (e.g., by preventing participants from processing the distractor), but not reverse it.

Method

Participants

We chose to collect usable data from 48 subjects for several reasons. The first and second reasons were the same as in Experiment 1. The third was that, in an analogous study of the CSE (Weissman et al., 2015, Experiment 3), the partial eta squared values for the CSE in the 166-ms SOA blocks and the 1,133-ms SOA blocks (0.63 and 0.41, respectively) were each larger than 0.36. G*Power estimates that 26 subjects would provide 95% power to observe an effect of that size (i.e., 0.36) at an α of .05. Fourth, in Experiment 1, the partial eta squared value for the PCE in the 166-ms SOA blocks was about 0.24, for which G*Power estimates that 45 subjects would provide 95% power at an α of .05. Fifth, since there was no significant difference in CSE magnitude between the 166-ms and 1,133-ms SOA blocks in our prior study above, we did not expect to observe a significant difference in the size of the PCE between the 166-ms and 933-ms SOA blocks.

One goal of the present experiment, though, was to determine whether the PCE is larger at the 166-ms SOA than at the 933-ms SOA. The attentional shift account's assumption that conflict drives the PCE predicts exactly such a result because the size of the congruency effect—an important index of conflict (Yeung et al., 2011)—is larger when the prime-probe SOA is short (e.g., 166 ms) relative to long (e.g., 1,000 ms; Weissman et al., 2015). What is the appropriate sample size for testing this hypothesis? Experiment 1 yielded a partial η^2 value of 0.12 for the difference in the PCE between the 166- and 0-ms SOAs. Fifty-seven participants would be required to achieve 80% power for observing such a difference with an α of .05.

However, we expected any difference in congruency effects between the 166- and 933-ms SOAs of Experiment 2 to be larger than the difference between the 166- and 0-ms SOAs of Experiment 1. The reason is that the congruency effect should be about 0 ms at the 933-ms SOA in Experiment 2 (cf. Weissman et al., 2015), rather than 41 ms at the 0-ms SOA in Experiment 1. The attentional shift account posits that a larger difference in conflict—indexed by a larger congruency effect at the 166-ms (vs. 933 ms) SOA—should lead to a larger increase of control (Botvinick et al., 2001). Thus, this account predicts a larger difference in PCE magnitude between the 166- and 933-ms SOAs of Experiment 2 than between the 166- and 0-ms SOAs of Experiment 1. As noted above, the latter difference was associated with a partial η^2 value of 0.12 in Experiment 1. Power analyses showed that for even a slightly larger partial η^2 value (0.15), 48 participants would provide 80% power at an α of .05. Therefore, we decided to collect usable data from 48 participants.

Fifty students from the University of Michigan's Psychology Subject Pool participated for course credit. We excluded the data from one participant who performed with less than 75% overall accuracy and from another participant who had difficulty completing the task due to a deficit with fine motor control. Thus, the final data analyses included data from 48 participants (16 male, 32 female; mean age, 19.0 years; age range: 18–28 years).

Stimuli and Apparatus

These were identical to those in Experiment 1.

Task

The task was identical to that of Experiment 1 with a single exception. We replaced the 0-ms SOA blocks with 933-ms SOA blocks. In the 933-ms SOA blocks, the prime (100 ms) and a longer blank screen (833 ms) preceded the probe (100 ms; Figure 3).

Experimental Design

The experimental design was identical to that of Experiment 1 with the exception that we replaced the 0-ms SOA blocks with 933-ms SOA blocks.

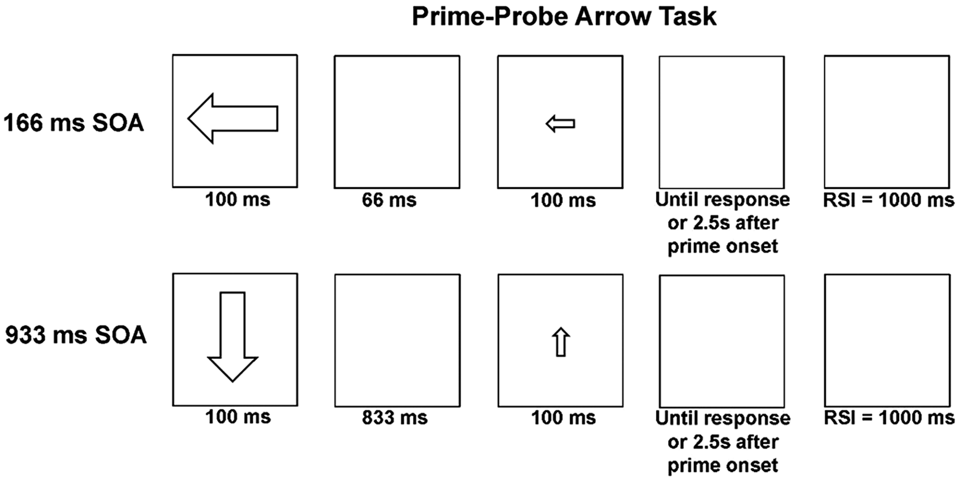
Procedure

The procedure was identical to that of Experiment 1.

Data Analyses

The data analyses were identical to those in Experiment 1 with the exception that we replaced the 0-ms SOA blocks with 933-ms SOA blocks. In the analysis of mean RT, outliers occurred in 3.8% of the trials. Errors and omitted responses occurred in 4.9% of the trials. Table 4 presents the conditional mean RTs and mean ERs in Experiment 2.

Figure 3
The Prime-Probe Arrow Task in Experiment 2



Note. At each SOA, the prime arrow appeared before the probe arrow. We instructed participants to press one of four keys to indicate the direction in which the second (i.e., probe) arrow points. The time beneath each box indicates the duration of the corresponding trial component. SOA = stimulus onset asynchrony; RSI = response-to-stimulus interval.

Table 4

Mean Reaction Times and Mean Error Rates (and Corresponding Standard Errors) in Experiment 2

		Reaction time				Error rate			
SOA		166 ms		933 ms		166 ms		933 ms	
Item type	Trial type	MC	MI	MC	MI	MC	MI	MC	MI
Inducer	Congruent	406 (6)	467 (7)	424 (7)	456 (9)	1.5 (0.3)	1.6 (0.5)	1.9 (0.3)	2.8 (0.8)
	Incongruent	527 (9)	487 (7)	462 (9)	431 (7)	17.2 (3.1)	3.3 (0.7)	4.0 (1.0)	1.9 (0.3)
	Cong effect	121	20	38	−25	15.7	1.7	2.1	−0.9
Diagnostic	Congruent	433 (7)	448 (6)	451 (7)	465 (8)	2.3 (0.5)	1.7 (0.3)	2.0 (0.4)	2.3 (0.4)
	Incongruent	529 (8)	508 (8)	458 (8)	451 (8)	7.7 (1.9)	4.7 (1.0)	2.7 (0.5)	1.8 (0.4)
	Cong effect	96	60	7	−14	5.4	3	0.7	−0.5

Note. Each parenthetical value indicates the standard error of the condition mean across participants. SOA = stimulus onset asynchrony; MC = mostly congruent blocks; MI = mostly incongruent blocks; Cong effect = congruency effect.

Transparency and Openness

The transparency and openness procedures were the same as in Experiment 1. The preregistration, task scripts, data analysis scripts, and raw data are available on the OSF (https://osf.io/kbdjp/).

Results

Inducer Items

Mean RT. There were two significant main effects. First, there was a main effect of SOA, $F(1, 47) = 32.54$, $p < .001$, $\eta_p^2 = 0.41$, $\mathrm{BF_I} = 21066.22$: Mean RT was longer at the 166-ms SOA (472 ms) than at the 933-ms SOA (443 ms). Second, there was a main effect of trial type, $F(1, 47) = 57.06$, $p < .001$, $\eta_p^2 = 0.55$, $\mathrm{BF_I} = 1.021 \times 10^7$: Mean RT was longer in incongruent trials (477 ms) than in congruent trials (438 ms).

There were also two significant interactions. First, there was a significant interaction between proportion congruency and trial type, $F(1, 47) = 233.11$, $p < .001$, $\eta_p^2 = 0.83$, $\mathrm{BF_I} = 3.722 \times 10^{16}$, indicating a PCE: The congruency effect was 83 ms larger in mostly congruent blocks (80 ms) than in mostly incongruent blocks (−3 ms). Second, there was an interaction between SOA and trial type, $F(1, 47) = 96.40$, $p < .001$, $\eta_p^2 = 0.67$, $\mathrm{BF_I} = 1.562 \times 10^{10}$, because the congruency effect was larger at the 166-ms SOA (71 ms) than at the 933-ms SOA (7 ms).

Finally, the three-way interaction was significant, $F(1, 47) = 16.83$, $p < .001$, $\eta_p^2 = 0.26$, $\mathrm{BF_I} = 440.23$ (Figure 4, top). The PCE was larger at the 166-ms SOA (101 ms; Figure 4, top left) than at the 933-ms SOA (63 ms; Figure 4, top right). Furthermore, the 63-ms PCE at the 933-ms SOA was significant, $F(1, 47) = 68.71$, $p < .001$, $\eta_p^2 = 0.59$, $\mathrm{BF_I} = 1.946 \times 10^{10}$, even though the 7-ms overall congruency effect at this SOA was not significant, $F(1, 47) = 1.2$, $p = .28$, $\eta_p^2 = 0.03$, $\mathrm{BF_I} = 0.32$. In particular, there was a positive 38-ms congruency effect in mostly congruent blocks, $F(1, 47) = 25.96$, $p < .001$, $\eta_p^2 = 0.36$, $\mathrm{BF_I} = 2514.06$, and a negative 25-ms congruency effect in mostly incongruent blocks, $F(1, 47) = 14.2$, $p < .001$, $\eta_p^2 = 0.23$, $\mathrm{BF_I} = 54.37$. No other effects were significant (all ps > .09).

Mean ER. All of the main effects were significant. First, there was a main effect of proportion congruency, $F(1, 47) = 23.72$, $p < .001$, $\eta_p^2 = 0.34$, $\mathrm{BF_I} = 385.09$: Mean ER was higher in mostly congruent blocks (6.2%) than in mostly incongruent blocks (2.4%). Second, there was a main effect of SOA, $F(1, 47) = 11.85$, $p < .001$, $\eta_p^2 = 0.20$, $\mathrm{BF_I} = 18.47$: Mean ER was higher at the 166-ms SOA (5.9%) than at the 933-ms SOA (2.7%). Note that in the analysis of mean RT for inducer items, we observed the opposite pattern: Faster responses at the 166-ms SOA than at the 933-ms SOA. These contrasting patterns may reflect a speed–accuracy trade-off. Third, there was a main effect of trial type, $F(1, 47) = 24.10$, $p < .001$, $\eta_p^2 = 0.34$, $\mathrm{BF_I} = 1251.64$: Mean ER was higher in incongruent trials (6.6%) than in congruent trials (2.0%).

All of the two-way interactions were significant. First, there was an interaction between proportion congruency and SOA, $F(1, 47) = 19.56$, $p < .001$, $\eta_p^2 = 0.29$, $\mathrm{BF_I} = 131.98$, because mean ER was much higher in mostly congruent versus mostly incongruent blocks at the 166-ms SOA (9.4% vs. 2.5%) whereas it was only slightly higher in mostly congruent versus mostly incongruent blocks at the 933-ms SOA (3.0% vs. 2.3%). Second, there was an interaction between proportion congruency and trial type, $F(1, 47) = 27.12$, $p < .001$, $\eta_p^2 = 0.37$, $\mathrm{BF_I} = 3314.39$, indicating a PCE. More specifically, the congruency effect was larger in mostly congruent blocks (8.9%) than in mostly incongruent blocks (0.4%). Third, there was an interaction between SOA and trial type, $F(1, 47) = 18.72$, $p < .001$, $\eta_p^2 = 0.29$, $\mathrm{BF_I} = 258.19$, because the congruency effect was larger at the 166-ms SOA (8.7%) than at the 933-ms SOA (0.7%).

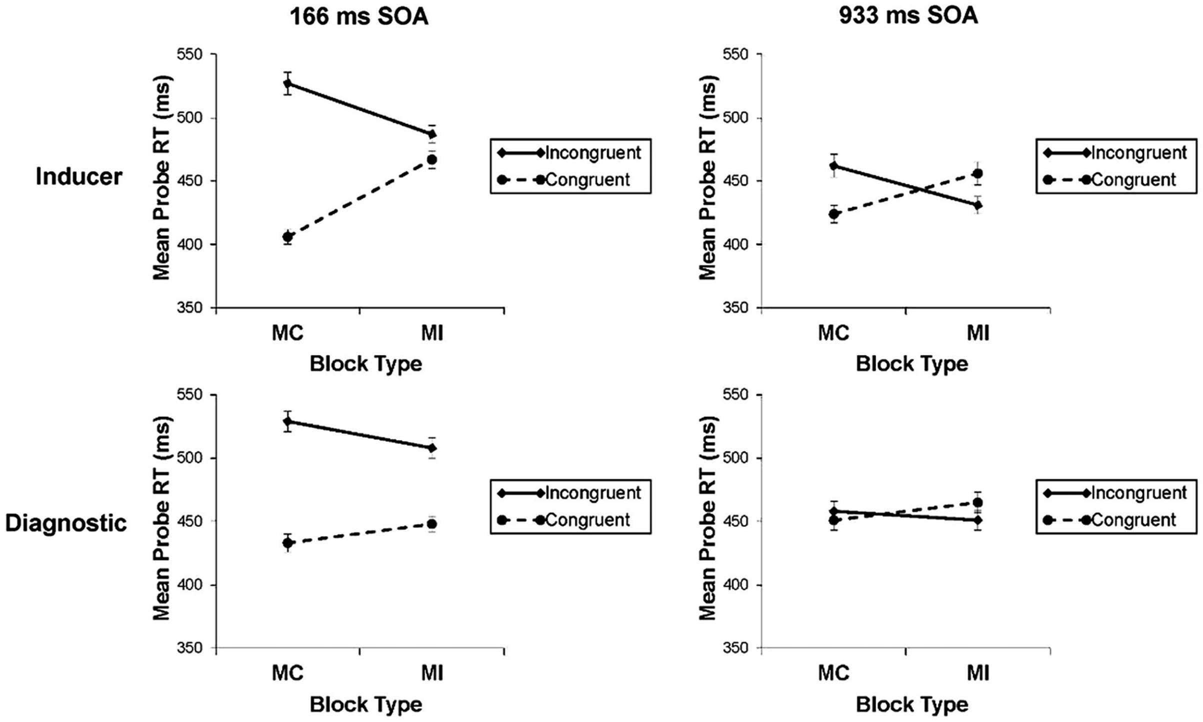
Finally, the three-way interaction was significant, $F(1, 47) = 13.75$, $p < .001$, $\eta_p^2 = 0.23$, $\mathrm{BF_I} = 1346.53$. The PCE was larger at the 166-ms SOA (14.0%) than at the 933-ms SOA (3.0%). Further, the 3.0% PCE at the 933-ms SOA was significant, $F(1, 47) = 6.72$, $p = .013$, $\eta_p^2 = 0.13$, $\mathrm{BF_I} = 8.22$, even though the overall congruency effect at this SOA was not significant, $F(1, 47) < 1$, $\mathrm{BF_I} = 0.277$. Indeed, although there was a significant positive 2.1% congruency effect in mostly congruent blocks, $F(1, 47) = 4.34$, $p = .043$, $\eta_p^2 = 0.09$, $\mathrm{BF_I} = 1.79$, there was a nonsignificant negative 0.9% congruency effect in mostly incongruent blocks, $F(1, 47) = 1.10$, $p = .30$, $\eta_p^2 = 0.02$, $\mathrm{BF_I} = 0.37$. No other effects were significant.

Diagnostic Items

Mean RT. There were two significant main effects. First, there was a significant main effect of SOA, $F(1, 47) = 23.43$, $p < .001$, $\eta_p^2 = 0.33$, $\mathrm{BF_I} = 1336.99$, because mean RT was longer at the 166-ms SOA (479 ms) than at the 933-ms SOA (456 ms). Second, there was a main effect of trial type, $F(1, 47) = 101.47$, $p < .001$, $\eta_p^2 = 0.68$, $\mathrm{BF_I} = 3.157 \times 10^{10}$, because mean RT was longer in incongruent trials (486 ms) than in congruent trials (449 ms).

Figure 4

Proportion Congruency Effects in Experiment 2



Note. Mean RT as a function of trial type (congruent, incongruent) and block type (MC = mostly incongruent, MI = mostly incongruent) plotted separately for each of the four combinations of SOA (166 ms, 0 ms) and item type (inducer, diagnostic). Positive and negative error bars indicate one standard error of the conditional mean across participants. SOA = stimulus onset asynchrony; RT = response time.

A pair of two-way interactions was significant. First, there was an interaction between proportion congruency and trial type, $F(1, 47) = 85.21$, $p < .001$, $\eta_p^2 = 0.64$, $\mathrm{BF_I} = 4.242 \times 10^7$, indicating a PCE: The congruency effect was 27 ms larger in mostly congruent blocks (51 ms) than in mostly incongruent blocks (24 ms). Second, there was an interaction between SOA and trial type, $F(1, 47) = 198.28$, $p < .001$, $\eta_p^2 = 0.81$, $\mathrm{BF_I} = 4.282 \times 10^{15}$, because the congruency effect was larger at the 166-ms SOA (78 ms) than at the 933-ms SOA (−4 ms).

Finally, the three-way interaction was significant, $F(1, 47) = 5.10$, $p = .029$, $\eta_p^2 = 0.10$, $\mathrm{BF_I} = 3.21$ (Figure 4, bottom). The PCE was larger at the 166-ms SOA (36 ms; Figure 4, bottom left) than at the 933-ms SOA (21 ms; Figure 4, bottom right). We note that the 21-ms PCE at the 933-ms SOA was significant, $F(1, 47) = 20.80$, $p < .001$, $\eta_p^2 = 0.31$, $\mathrm{BF_I} = 504.27$, even though the congruency effect at this SOA (−4 ms) was not significant, $F(1, 47) < 1$, $\mathrm{BF_I} = 0.43$. Further, this 21-ms PCE was associated with a positive (but not significant) 7-ms congruency effect in mostly congruent blocks, $F(1, 47) = 1.64$, $p = .21$, $\eta_p^2 = 0.03$, $\mathrm{BF_I} = 0.43$, and a negative (i.e., reverse) and significant 14-ms congruency effect in mostly incongruent blocks, $F(1, 47) = 9.29$, $p = .004$, $\eta_p^2 = 0.17$, $\mathrm{BF_I} = 9.89$. No other effects were significant (all ps > .20).

Mean ER. All of the main effects were significant. First, there was a main effect of proportion congruency, $F(1, 47) = 5.72$, $p = .021$, $\eta_p^2 = 0.11$, $\mathrm{BF_I} = 1.40$: Mean ER was lower in mostly incongruent blocks (2.6%) than in mostly congruent blocks (3.7%). Second, there was a main effect of SOA, $F(1, 47) = 6.58$, $p = .014$, $\eta_p^2 = 0.12$, $\mathrm{BF_I} = 3.86$: Mean ER was higher at the 166-ms SOA (4.1%) than at the 933-ms SOA (2.2%). Note again that in the analysis of mean RT for diagnostic items, we observed the opposite pattern: Faster responses at the 166-ms SOA than at the 933-ms SOA. Again, these contrasting patterns may reflect a speed–accuracy trade-off. Third, there was a main effect of trial type, $F(1, 47) = 9.95$, $p = .003$, $\eta_p^2 = 0.18$, $\mathrm{BF_I} = 13.38$, because mean ER was higher in incongruent trials (4.2%) than in congruent trials (2.1%).

A pair of two-way interactions was significant. First, there was an interaction between proportion congruency and trial type, $F(1, 47) = 5.58$, $p = .022$, $\eta_p^2 = 0.11$, $\mathrm{BF_I} = 1.44$, because the congruency effect was larger in mostly congruent blocks (3.0%) than in mostly incongruent blocks (1.3%). Second, there was an interaction between SOA and trial type, $F(1, 47) = 8.35$, $p = .006$, $\eta_p^2 = 0.15$, $\mathrm{BF_I} = 7.27$, because the congruency effect was larger at the 166-ms SOA (4.2%) than at the 933-ms SOA (0.1%). No other effects were significant (all ps ≥ 0.08).

Discussion

The results of Experiment 2 were clear-cut. We focus our discussion of these results on the diagnostic items, but note that we observed similar results for the inducer items. First, we observed a PCE without an overall congruency (i.e., conflict) effect at the 933-ms SOA. Second, the PCE at the 933-ms SOA was associated with a positive congruency effect in mostly congruent blocks and with a negative (reverse) congruency effect in mostly incongruent blocks. Third, and finally, we observed a larger PCE at the 166-ms SOA, wherein the congruency effect was relatively large, than at the 933-ms SOA, wherein the congruency effect was absent.

The PCE that we observed at the 166-ms SOA replicates the result pattern from Experiment 1 for that SOA and, as we discussed for that experiment, is consistent with both the response modulation account and the attentional shift account. In contrast, the PCE that we observed at the 933-ms SOA and the associated negative congruency effect in mostly incongruent blocks are more consistent with the response modulation account than with the attentional shift account. First, only the response modulation account predicts a PCE without an overall congruency effect. Second, a negative congruency effect can arise from a modulation (e.g., inhibition) of response activation related to the prime but not from a shift of attention toward the target (since attending exclusively to the probe would cause, at best, an elimination—rather than a reversal—of the congruency effect). These findings support the view that a modulation of response activation contributes to the PCE in the prime-probe task at long SOAs.

The larger PCE that we observed at the 166-ms (vs. 933 ms) SOA has more than one possible interpretation. First, since the overall congruency effect was larger at the 166-ms (vs. 933 ms) SOA, this finding may indicate that a conflict-triggered shift of attention produces the PCE at the 166-ms SOA while a modulation of response activation produces the PCE at the 933-ms SOA. Second, this finding may indicate that a response modulation mechanism produces the PCE at both SOAs but produces larger effects at the 166-ms SOA than at the 933-ms SOA. Indeed, since control is costly in many views (Bugg, 2014; Shenhav et al., 2013), any type of control mechanism may be less likely to operate as the SOA (and, hence, the need to sustain control) increases. Third, this finding may reflect contributions from both an attentional shift *and* a modulation of response activation at the 166-ms SOA. Additional studies will be necessary to distinguish between these three possible interpretations. Whatever the outcome, the present findings clearly support the response modulation account of the PCE at the 933-ms SOA.

Finally, one may wonder whether inhibition of return (IOR; Posner & Cohen, 1984) contributes to the negative congruency effect that we observed in mostly incongruent blocks at long (e.g., 933 ms) SOAs. IOR reflects cognitive processes that eventually (i.e., at long SOAs) inhibit a location to which spatial attention moves in a *reflexive* (i.e., bottom-up) manner. Therefore, if the prime arrow in each trial leads participants to reflexively orient spatial attention in the direction the arrow points (e.g., to the left of fixation if the arrow points left), IOR could make it relatively difficult to identify a probe arrow that points in the same direction 933 ms later because the arrowhead appears in an inhibited location. In this way, IOR could selectively slow RTs in congruent (vs. incongruent) trials, thus contributing to the negative congruency effect (note that IOR should not contribute to the PCEs that we observed as IOR should be similar in mostly congruent and mostly incongruent blocks). Critically, IOR occurs only when spatial cues are uninformative (Posner & Cohen, 1984). In the present tasks, however, the prime arrows (i.e., spatial cues) are—on average—highly informative. In mostly congruent blocks, they usually predict probe arrows that point in the same (congruent) direction. In mostly incongruent blocks, they usually predict probe arrows that point in the opposite (incongruent) direction. One might argue that only the inducer prime arrows are informative in these ways. The cognitive system, however, treats the diagnostic prime arrows as if they are informative as well, presumably because they appear in the same blocks as the informative inducer prime arrows, as indexed by the robust PCEs that we observe in diagnostic trials. Therefore, in our view, IOR is unlikely to contribute to any of the negative congruency effects that we observed at long SOAs.

Experiment 3

The goal of Experiment 3 was to determine whether the contribution to cognition of the response modulation mechanism underlying the PCE at long SOAs is broader than minimizing distraction from irrelevant stimuli. To this end, we investigated whether the PCE appears not only in the standard prime-probe task that we employed in Experiments 1 and 2 but also in the modified prime-probe task, wherein participants respond to both the prime and the probe (Weissman et al., 2017). Such a finding would indicate that the control processes underlying the PCE at long SOAs in the prime-probe task operate in the complete absence of irrelevant stimuli (i.e., in the absence of manipulated distraction). It would also complement prior results indicating that the CSE appears in the modified prime-probe task (Grant & Weissman, 2019, 2023; Weissman, 2019). In particular, such a finding would show that the mechanism underlying the PCE at long SOAs combines information about block-wide congruency (e.g., mostly congruent) with the identity of the prime (e.g., left arrow) to prepare a response to the upcoming probe (e.g., F key for left arrow), regardless of whether the prime is a distractor or a target. Such an outcome would clearly suggest that, analogous to the control mechanism underlying the CSE at long SOAs, the control mechanism underlying the PCE at long SOAs makes a broader contribution to cognition than coping with distraction from irrelevant stimuli.

We note that such a contribution might involve learning abstract relationships between stimuli and/or responses (Weissman et al., 2020). To produce a PCE for the diagnostic items in the modified prime-probe task, control processes must learn about relatively abstract relationships between inducer primes and inducer probes. In mostly congruent blocks, control processes must learn that each inducer prime and each inducer probe are usually "similar" in terms of their perceptual attributes, meaning, or the responses they signal. In mostly incongruent blocks, control processes must learn that each inducer prime and each inducer probe are usually "dissimilar" in one or more of these ways. To produce a PCE for the diagnostic stimuli, control processes must form an abstract expectation that each upcoming probe will be "similar" (in mostly congruent blocks) or "dissimilar" (in mostly incongruent blocks) to the preceding prime, which applies not only to the biased inducer stimuli but also to the unbiased diagnostic stimuli. Observing a PCE for the diagnostic items in the modified prime-probe task would clearly fit with a control mechanism that learns about abstract relationships between stimuli and/or responses.

We also investigated whether the PCE is larger in the modified (vs. standard) prime-probe task. If the PCE indexes an accumulation of CSEs across multiple trials (which is sometimes suggested; see, e.g., Braem et al., 2019), this result would appear likely because the CSE is larger in the modified (vs. standard) prime-probe task (Grant & Weissman, 2019, 2023). The typical explanation builds on the view that the CSE results from retrieving an episodic memory that specifies the previous trial's congruency (Egner, 2014; Spapé & Hommel, 2008;

Weissman et al., 2016). Specifically, this episodic retrieval process is disrupted in the standard prime-probe task by switching between different stimulus–response mappings for the prime ("do not respond") and the probe ("respond"; Grant & Weissman, 2019, 2023). In contrast, if the view that the PCE at long SOAs indexes conflict-independent, proactive control processes that modulate prime-related response activation before the probe appears (Logan, 1985; Logan & Zbrodoff, 1979) could make a prediction for the modified prime-probe task, it would not necessarily predict a larger PCE in that version of the task compared to the standard version. The reason is that, similar to other views of the PCE (Bugg, 2014; Bugg & Crump, 2012; Egner, 2014), this view posits that adjustments of sustained proactive control vary with the relative proportions of congruent and incongruent trials in a block (i.e., mostly congruent vs. mostly incongruent) more than they vary with the previous trial's congruency. Consequently, since the relative *proportions* of congruent and incongruent trials vary similarly across blocks for the standard and modified prime-probe tasks, the PCE may not differ between these tasks.

Method

Participants

We chose to collect usable data from 48 participants for the following reason. In a prior study (Grant & Weissman, 2019), the larger CSE when participants responded to both arrows relative to only the probe arrow was associated with a partial η^2 value of 0.326. Power analyses in G*Power revealed that 32 subjects would be sufficient to observe such an effect size with 95% power at an α level of .05. Ultimately, however, we decided to collect usable data from 48 participants. We reasoned that this sample size would not only increase power but also be consistent with the sample sizes in Experiments 1 and 2. Unlike in Experiments 1 and 2, participants could participate only if they did not self-report a history of seizures, concussions, neuropsychiatric diseases or disorders, or head trauma. As in Experiments 1 and 2, participants also needed to self-report normal or corrected-to-normal (e.g., with glasses) vision and hearing.

Fifty-two students from the University of Michigan's Psychology Subject Pool participated for course credit. We excluded the data from three participants who performed with less than 75% overall accuracy and from one participant who did not complete the experiment. Thus, the final data analyses included data from 48 participants (13 male, 35 female; mean age, 19.0 years; age range: 18–21 years).

Stimuli and Apparatus

These were identical to those in Experiments 1 and 2.

Task

The task was identical to that in Experiment 2 with three exceptions. First, we increased the prime-probe SOA in *all* trials to 1,133 ms by changing the duration of the blank screen separating the prime from the probe to 1,033 ms (i.e., there was no contrast between a short SOA and a long SOA in this experiment). By increasing the SOA, we sought to provide participants with an average RSI of approximately 600 ms before the probe appeared in the modified prime-probe task blocks. Indeed, similar to mean probe RTs, mean *prime* RTs in the modified prime-probe task are typically less than 500 ms. Second, we required participants to respond to both the prime and the probe in half the blocks but only to the probe in the other half of blocks. We counterbalanced the order of these two block types across participants. Third, if participants responded to the prime (in the modified prime-probe task) or to the probe (in both the standard and the modified prime-probe tasks) after the 900-ms response deadline, the word "Error" appeared during the RSI rather than the words "Too Slow" as in Experiments 1 and 2. We reasoned that this change might aid performance by simplifying the feedback that participants received (i.e., no feedback if a correct response occurred within the 900-ms deadline, "Error" otherwise). Finally, the word "Error" also appeared during the RSI if the participant responded incorrectly to the prime or to the probe in either task within the 900-ms response deadline. Figure 5 illustrates the task that we employed in Experiment 3.

Experimental Design

The experimental design was identical to that of Experiment 2 with two exceptions. First, we eliminated the four "adjustment" blocks. We reasoned that doing so would save time and not be problematic as many studies do not even include such blocks (e.g., Spinelli & Lupker, 2023). Second, given that we used a 1,133-ms SOA in all trials, we replaced the factor prime-probe SOA (166 ms, 933 ms) with the factor task type (standard prime-probe, modified prime-probe). Note that, in the modified prime-probe task, we regard each prime-probe pair as appearing in a single trial even though both the prime and the probe within each prime-probe pair require a response. Thus, in this task, the trial type (congruent or incongruent) refers to the congruency between the prime and the probe within each trial just as it does in the standard prime-probe task.

Procedure

The procedure was identical to that of Experiment 2 with a single exception. The research assistant reentered the testing chamber halfway through the experiment to review the new task instructions with the participant. In Experiments 1 and 2, we did not feel this was necessary because participants responded only to the probe in all blocks. In Experiment 3, however, participants were required to respond to the prime *and* the probe in half the blocks but only to the probe in the other half of blocks. By explaining the new response requirements at the halfway point, the research assistant helped to ensure that participants understood the task instructions.

Data Analyses

The data analyses involving mean probe RT and mean probe ER were identical to those in Experiment 2 with three exceptions. First, we replaced the factor prime-probe SOA (166 ms, 933 ms) with the factor task type (standard prime-probe, modified prime-probe). Second, for the modified prime-probe task, we analyzed mean probe RT and mean probe ER only in trials wherein participants responded correctly to the prime within 900 ms. Table 5 presents the conditional mean probe RTs and mean probe ERs in Experiment 3.[5]

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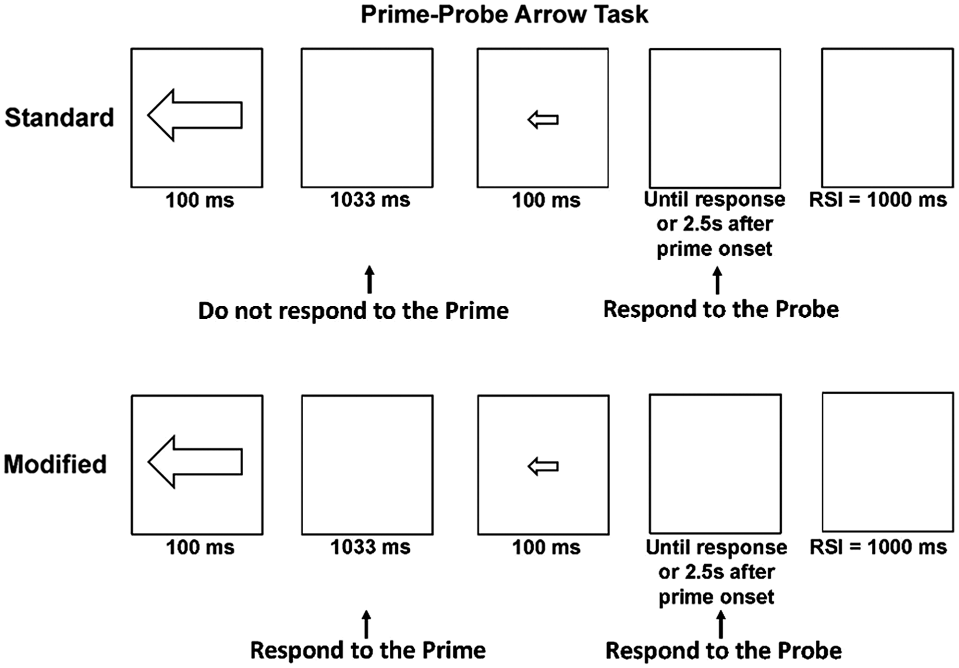
[5] We also analyzed mean prime RT and mean prime ER as a function of item type (inducer, diagnostic). Mean prime RT was 454 and 458 ms for the inducer and diagnostic stimuli, respectively. Therefore, on average, a 677-ms RSI separated the response to the prime from the onset of the probe 1,133 ms into the trial (i.e., 1,133 ms − 456 ms = 677 ms). Mean prime ER was 4.8% and 4.0% for the inducer and diagnostic stimuli, respectively.

Figure 5

The Prime-Probe Arrow Task in Experiment 3



Note. In the standard version, we instructed participants to press one of four keys to indicate the direction in which the second (i.e., probe) arrow points. In the modified version, we instructed participants to (a) press one of four keys to indicate the direction in which the first (i.e., prime) arrow points and then (b) press one of four keys to indicate the direction in which the second (i.e., probe) arrow points. The time beneath each box indicates the duration of the corresponding trial component. RSI = response-to-stimulus interval.

Transparency and Openness

These were identical to those in Experiments 1 and 2. The preregistration, task scripts, data analysis scripts, and raw data are available on the OSF (https://osf.io/sdkyt/).

Results

Inducer Items

Mean Probe RT. There were two significant effects. First, there was a main effect of task, $F(1, 47) = 53.67$, $p < .001$, $\eta_p^2 = 0.53$, $BF_I = 4.001 \times 10^6$, because mean RT was longer in the standard prime-probe task (454 ms) than in the modified prime-probe task (416 ms). Second, there was an interaction between proportion congruency and trial type, $F(1, 47) = 104.95$, $p < .001$, $\eta_p^2 = 0.69$, $BF_I = 6.327 \times 10^{10}$, because the congruency effect was larger in mostly congruent blocks, 34 ms; $F(1, 47) = 47.34$, $p < .001$, $\eta_p^2 = 0.50$, $BF_I = 674909.69$, than in mostly incongruent blocks, −19 ms; $F(1, 47) = 15.61$, $p < .001$, $\eta_p^2 = 0.25$, $BF_I = 79.02$. No other effects were significant (all *p*s > .055), including the three-way interaction ($p = .069$, $BF_I = 0.904$; Figure 6, top): The PCE did not significantly differ between the standard prime-probe task (46 ms;

Table 5

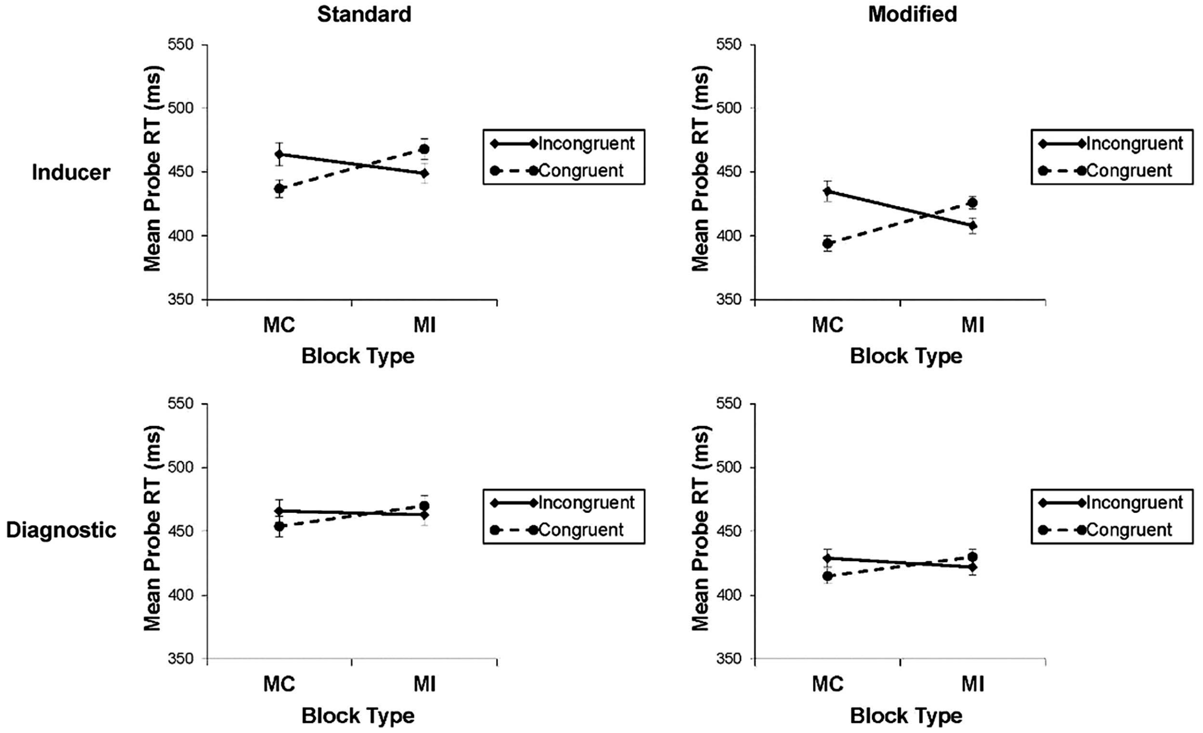
Mean Reaction Times and Mean Error Rates (and Corresponding Standard Errors) in Experiment 3

		Reaction time				Error rate			
		Standard		Modified		Standard		Modified	
Item type	Trial type	MC	MI	MC	MI	MC	MI	MC	MI
Inducer	Congruent	437 (7)	468 (8)	394 (6)	426 (5)	2.3 (0.3)	3.9 (1.0)	2.2 (0.3)	8.3 (1.7)
	Incongruent	464 (8)	449 (8)	435 (7)	408 (6)	2.1 (0.7)	1.8 (0.3)	8.0 (1.5)	2.3 (0.3)
	Cong effect	27	−19	41	−18	−0.2	−2.1	5.8	−6
Diagnostic	Congruent	454 (8)	470 (8)	415 (6)	430 (6)	2.0 (0.4)	2.4 (0.5)	3.9 (0.6)	6.1 (0.8)
	Incongruent	466 (9)	463 (8)	429 (7)	422 (6)	2.6 (0.5)	2.4 (0.4)	5.6 (0.7)	4.5 (0.8)
	Cong effect	12	−7	14	−8	0.6	0	1.7	−1.6

Note. Each parenthetical value indicates the standard error of the condition mean across participants. Standard = standard prime-probe task; Modified = modified prime-probe task. MC = mostly congruent blocks; MI = mostly incongruent blocks; Cong effect = congruency effect.

Figure 6

Proportion Congruency Effects in Experiment 3



Note. Mean RT as a function of trial type (congruent, incongruent) and block type (MC = mostly congruent, MI = mostly incongruent) plotted separately for each of the four combinations of task (standard, modified) and item type (inducer, diagnostic). Positive and negative error bars indicate one standard error of the conditional mean across participants. RT = response time.

Figure 6, top left) and the modified prime-probe task (59 ms; Figure 6, top right).

Mean Probe ER. There were three significant effects. First, there was a main effect of task, $F(1, 47) = 15.19, p < .001, \eta_p^2 = 0.24$, $BF_I = 55.32$, because mean ER was higher in the modified prime-probe task (5.2%) than in the standard prime-probe task (2.5%). Note that in the analysis of mean RT for inducer items, we observed the opposite pattern (i.e., slower responses in the standard task than in the modified task). Thus, this pattern most likely reflects a speed–accuracy trade-off. Second, there was an interaction between proportion congruency and trial type, $F(1, 47) = 31.26$, $p < .001$, $\eta_p^2 = 0.40$, $BF_I = 9808.63$, because the congruency effect was larger in mostly congruent blocks (2.9%) than in mostly incongruent blocks (−4.0%). Third, the three-way interaction was significant, $F(1, 47) = 16.62$, $p < .001$, $\eta_p^2 = 0.26$, $BF_I = 23374.44$. More specifically, the PCE was larger in the modified prime-probe task, in which it was significant, 11.8%; $F(1, 47) = 30.37, p < .001, \eta_p^2 = 0.39, BF_I = 5.317 \times 10^6$, than in the standard prime-probe task, in which it was not significant, 1.9%; $F(1, 47) = 2.92, p = .094, \eta_p^2 = 0.06, BF_I = 1.08$. No other effects were significant (all *p*s > .34).

Diagnostic Items

Mean Probe RT. There were three significant effects. First, there was a main effect of proportion congruency, $F(1, 47) = 5.14$, $p = .028$, $\eta_p^2 = 0.10$, $BF_I = 1.46$, because mean RT was longer in mostly incongruent blocks (446 ms) than in mostly congruent blocks (441 ms). Second, there was a main effect of task, $F(1, 47) = 44.57, p < .001, \eta_p^2 = 0.49, BF_I = 338049.02$, because mean RT was longer in the standard prime-probe task (463 ms) than in the modified prime-probe task (424 ms). Third, there was an interaction between proportion congruency and trial type, $F(1, 47) = 52.92$, $p < .001$, $\eta_p^2 = 0.53$, $BF_I = 151103.74$, because the congruency effect was larger in mostly congruent blocks, 13 ms; $F(1, 47) = 12.05, p = .001, \eta_p^2 = 0.20, BF_I = 27.28$, than in mostly incongruent blocks, −8 ms; $F(1, 47) = 5.81$, $p = .020$, $\eta_p^2 = 0.11$, $BF_I = 1.98$. No other effects were significant (all *p*s > .40), including the three-way interaction ($p > .74$; $BF_I = 0.23$; Figure 6, bottom) because the PCE did not significantly differ between the standard prime-probe task (19 ms; Figure 6, bottom left) and the modified prime-probe task (22 ms; Figure 6, bottom right).

Mean Probe ER. There were two significant effects. First, there was a significant main effect of task, $F(1, 47) = 30.00$, $p < .001$, $\eta_p^2 = 0.39$, $BF_I = 10147.40$, because mean ER was higher in the modified prime-probe task (5.0%) than in the standard prime-probe task (2.3%). Note, again, that in the analysis of mean RT for diagnostic items, we observed the opposite pattern (i.e., slower responses in the standard task than in the modified task), indicating a potential speed–accuracy trade-off. Second, there was an interaction between proportion congruency and trial type, $F(1, 47) = 12.00$, $p < .001, \eta_p^2 = 0.203, BF_I = 10.92$, because the congruency effect was larger in mostly congruent blocks, 1.2%; $F(1, 47) = 4.63, p = .037$,

$\eta_p^2 = 0.09$, $\mathrm{BF_I} = 0.39$, than in mostly incongruent blocks, −0.8%; $F(1, 47) = 3.35$, $p = .073$, $\eta_p^2 = 0.07$, $\mathrm{BF_I} = 0.49$. No other effects were significant (all *p*s > .063), although the PCE was numerically larger in the modified prime-probe task (3.3%) than in the standard prime-probe task (0.6%).

Discussion

The results of Experiment 3 indicate that the response modulation mechanism underlying the PCE at relatively long SOAs makes a broader contribution to cognition than minimizing distraction from irrelevant stimuli. We observed a significant PCE not only in the standard prime-probe task, wherein the prime serves as a distractor, but also in the modified prime-probe task, wherein the prime serves as an initial target. This outcome suggests that the mechanism underlying the PCE at long SOAs combines (a) knowledge of the sequential regularities in a task with (b) the identity of an initial stimulus—regardless of whether it is task-relevant or task-irrelevant—to form an expectation about an upcoming stimulus and/or response. That is, this outcome suggests that the mechanism above makes a relatively broad contribution to cognition, possibly related to learning abstract relationships between stimuli and/or responses (e.g., similar vs. dissimilar; Weissman et al., 2020).

We also found that the PCE associated with diagnostic trials does not differ between the modified and standard prime-probe tasks. This result further suggests that the same mechanism underlies the PCE in the standard and modified prime-probe tasks as different mechanisms might produce different-sized PCEs. This finding, however, contrasts with prior data showing that the CSE is larger in the modified (vs. standard) prime-probe task (Grant & Weissman, 2019, 2023). Hence, this result fits with the view that the PCE and the CSE index somewhat distinct processes that operate at long and short timescales, respectively (Torres-Quesada et al., 2013, 2014).

What is the precise distinction between these processes? One possibility is that PCEs and CSEs index control processes that adapt to high and low levels of volatility, respectively (Egner, 2014; Jiang et al., 2014). When trial congruency changes frequently (high volatility), the system predicts a repetition of the previous trial's congruency because more remote trials provide outdated information (cf. Behrens et al., 2007). Thus, as we described earlier, trial-by-trial learning—driven by retrieving an episodic memory of the previous trial (Egner, 2014)—exerts a relatively large influence on performance as indexed by transient changes in control (i.e., the CSE). Since, as we also described earlier, such episodic retrieval is greater in the modified prime-probe task than in the standard prime-probe task (Grant & Weissman, 2019, 2023), the CSE is larger in the modified (vs. standard) prime-probe task. When trial congruency changes less frequently (low volatility), the system predicts a trial whose congruency (e.g., incongruent) matches the block-wide congruency statistics (e.g., mostly incongruent) as these statistics provide reliable information about the next trial. Thus, learning across an entire block of trials—rather than trial-by-trial learning of the sort described above—exerts a relatively large influence on performance as indexed by sustained changes in proactive control (i.e., the PCE). The PCE is therefore similar in the modified and standard prime-probe tasks. Consistent with the view that the PCE and CSE index distinct adaptive control mechanisms, these effects can vary somewhat independently (e.g., a PCE can occur without a CSE; Torres-Quesada et al., 2013, 2014).

Finally, we note that—as for the 933-ms SOA in Experiment 2—a PCE for diagnostic items appeared without an overall congruency effect at the 1,133-ms SOA. This outcome once again fits with the response modulation account of the PCE at long SOAs but not with the attentional shift account. Indeed, the absence of an overall congruency effect indicates that incongruent trials do not evoke greater conflict than congruent trials (Yeung et al., 2011). Consequently, there is no heightened conflict in incongruent (vs. congruent) trials to trigger an attentional shift toward the target (Botvinick et al., 2001).

Experiment 4

Up to this point, we have argued that the PCE at long SOAs provides evidence for the response modulation account. There is, however, another account—the congruency switch account (Schmidt & De Houwer, 2011)—that could also predict a PCE at long SOAs. According to this account, congruent and incongruent trials require different mnemonic processes. A congruent trial in the prime-probe task, for example, requires processes that encode a single response (e.g., left middle finger) and bind that response to both the prime (e.g., left arrow) and the probe (e.g., left arrow). An incongruent trial, however, requires processes that encode two responses (e.g., left middle finger and right index finger) and bind each response to a different stimulus (e.g., to a left arrow prime and a right arrow probe). Critically, switching between congruency-specific mnemonic processes impairs performance. Performance for a given trial type (e.g., congruent) is, therefore, worse when participants usually switch to that trial type (e.g., in mostly incongruent blocks) than when they do not usually switch to that trial type (e.g., in mostly congruent blocks). Consequently, "congruency switch costs" could engender a larger congruency effect in mostly congruent blocks than in mostly incongruent blocks (i.e., a PCE).

The goal of Experiment 4 was to seek evidence for the response modulation account of the PCE at long SOAs that the congruency switch account cannot explain. Although the response modulation and congruency switch accounts can both explain the present PCEs, they make different predictions about *when* the processes that produce these PCEs occur. The response modulation account posits that control processes combine information about block-wide congruency statistics (e.g., mostly congruent) with the identity of the prime (e.g., up arrow) to prepare a response to the upcoming probe (e.g., J key for up arrow) *before* the probe appears. In contrast, the congruency switch account posits a congruency switch cost only *after* the probe appears, as only after probe onset can subjects establish the current trial's congruency.

In a recent study, the first author employed force-sensitive keys to investigate these two accounts of the CSE in the modified prime-probe arrow task (Weissman, 2019). As expected, the mean RT data yielded a robust CSE. Critically, just before the probe appeared, there was a CSE-like effect in finger force. This effect involved systematic changes in preprobe force on two response keys. We refer to these keys as the prime-congruent key (i.e., the key corresponding to the direction cued by the prime—e.g., the left key for a "Left" arrow prime) and the prime-incongruent key (i.e., the key corresponding to the direction opposite to the direction cued by the prime—e.g., the right key for a "Left" arrow prime). Critically, mean preprobe force was greater on the prime-congruent key than on the prime-incongruent key after congruent trials while the opposite pattern appeared after incongruent trials. That is, there was an interaction between previous trial congruency (congruent, incongruent) and response key (prime-congruent, prime-incongruent) with mean preprobe force serving as the dependent measure. This outcome is more consistent with the response modulation account than with the congruency switch account because only the former account predicts systematic changes in preprobe force.

In Experiment 4, we employ a similar approach to seek evidence for the response modulation account of the PCE at long SOAs that the congruency switch account cannot explain. The response modulation account posits that control processes combine information about block-wide congruency with the identity of the prime to prepare a congruent or incongruent response to the upcoming probe *before* the probe appears. Therefore, analogous to its predictions for the CSE, the response modulation account predicts an interaction between block type (mostly congruent, mostly incongruent) and response key (prime-congruent, prime-incongruent) with mean preprobe force serving as the dependent measure. The congruency switch account, on the other hand, does not predict such changes in preprobe force. According to this account, the processes that lead to congruency switch costs occur only *after* the probe appears.

Method

Participants

In Experiment 3, the overall PCE in mean probe RT for diagnostic items (averaged across the standard and modified prime-probe tasks, which produced equivalent PCEs) yielded a partial η^2 value of 0.53. Power analyses in G*Power showed that 15 subjects would be sufficient to observe this effect with 95% power ($\alpha = .05$).

The present study of the PCE in the modified prime-probe task asks whether preprobe force on the prime-congruent and prime-incongruent keys varies with previous trial congruency. Thus, it is important to estimate the effect size for such changes in preprobe force. In a prior study of the CSE in the modified prime-probe task that measured preprobe force (Weissman, 2019), the partial eta squared value for the force-related interaction of interest (0.506) was about 60% of the corresponding value for the CSE in mean probe RT (0.839). If the partial eta squared value for the behavioral PCE in the present study of the modified prime-probe task equals 0.53 as in Experiment 3, then 60% of this value would yield a partial η^2 value of 0.32 for the force-related interaction of interest. Power analyses in G*Power showed that 31 subjects would be sufficient to observe such an effect size with an α of .05. Ultimately, we chose to collect usable data from 48 participants. We reasoned that this sample size would provide additional power (in fact, over 99% power) and be consistent with the sample sizes in Experiments 1–3.

Forty-nine students from the University of Michigan's Psychology Subject Pool participated for course credit. We excluded the data from one participant for whom the experiment crashed due to a programming error. Thus, the final data analyses included data from 48 participants (18 male, 29 female, 1 not known; mean age, 19.0 years; age range: 18–22 years).

Stimuli and Apparatus

These were identical to those in Experiments 1–3 with a single exception. We employed custom response boxes to collect analog and digital measures of response force in a continuous fashion (i.e., at 500 Hz) throughout the experiment, rather than standard Windows PC keyboards. Analog response force changes continuously with finger pressure while digital response force is recorded only when a response key is fully pressed (response force = 60 cN). Each box has five force-sensitive keys that measure analog and digital force and two standard keys that measure only digital force. The five force-sensitive keys (F, G, J, K, and N) are spaced as on a QWERTY keyboard. Each key reliably detects analog changes in mass as small as 100 mg. The two standard keys (space bar and escape) appear at the bottom and top left corner of the box. We use custom Python software to transfer information between the response box and PsychoPy. Weissman (2019) provides a more detailed, technical description of the response boxes.

Before starting the study, we calibrated each force-sensitive key. This involved recording the load cell (i.e., key) output for 1 g, 2 g, 5 g, 10 g, and 20 g masses and using linear regression to determine the slope of the best-fitting line relating mass to load cell output. We then used this slope to convert mass to centinewtons (cN) as follows: $\text{cN} = 100 \times (\text{mass in kg} \times 9.8\ \text{m/s}^2)$. To check whether each key remained functional throughout the study, we recorded the load cell output on each key with (a) no mass and (b) a 5-g or 20-g mass before running every participant.

Task

The task was identical to that in Experiment 3 with a few exceptions. First, we employed only the modified prime-probe task. Second, while each half of the experiment still began with a 32-trial practice block, there were only five 64-trial blocks of mostly congruent trials in one half of the experiment and five 64-trial blocks of mostly incongruent trials in the other half. We counterbalanced across participants whether the mostly congruent or mostly incongruent blocks appeared in the first or second half of the experiment, respectively. Third, rather than using a 1,000-ms RSI, we used a constant trial duration of 3 s as in Weissman (2019). We reasoned this change would allow more time for force to return to baseline levels between trials. Specifically, since probe onset occurs at 1,133 ms in the modified prime-probe task and since mean RT is approximately 400–500 ms, a 3,000-ms trial duration would allow about 1,500 ms on average for force to return to baseline as compared to only 1,000 ms for a 1,000-ms RSI. Finally, error feedback appeared only during the final 200 ms of each trial as in Weissman (2019).

Experimental Design

The experimental design was identical to that of Experiment 3 with the exception that we employed only the modified prime-probe task. Thus, there were only three factors: item type (inducer, diagnostic), block type (mostly congruent, mostly incongruent), and trial type (congruent, incongruent).

Procedure

The procedure was identical to that in Experiment 3.

Data Analyses

The analyses of mean RT and mean ER were identical to those in Experiment 3 with two exceptions. First, since we only employed the modified prime-probe task, there were only two factors in each repeated-measures ANOVA: (1) block type (mostly congruent, mostly incongruent) and (2) trial type (congruent, incongruent). Second, in addition to the trial types that we excluded in the prior experiments, we excluded (a) a small subset of trials in which a malfunction produced a negative or absent prime or probe RT (0.67% of trials) and (b) trials following such "negative/absent RT" trials (0.47% of trials). Table 6 presents the conditional mean RTs and mean ERs for the probes in Experiment 4.

The analyses of mean response force were similar to those in Weissman (2019). First, we collected response force continuously at 500 Hz in the experiment. Second, we computed mean force across 100 time points, which corresponded to roughly 0–200 ms before probe onset, in each of the four combinations of block type (mostly congruent, mostly incongruent) and response key (prime-congruent, prime-incongruent), separately for each participant.[6] Third, we conducted a repeated-measures ANOVA to determine whether there was an interaction between block type and response key with mean preprobe force serving as the dependent measure. We note that these analyses compared preprobe force for two *keys* (i.e., the prime-congruent key vs. the prime-incongruent key) but not for two trial types (i.e., congruent vs. incongruent). Whether the *trial* was ultimately congruent or incongruent was not relevant here, because we compared force after prime onset but *before* probe onset.

In the analyses of mean force, we excluded (a) trials with an incorrect or omitted response to the prime and (b) trials after trials with an incorrect or omitted response to either the prime or the probe. We did not exclude trials based on the current probe response, which had not yet occurred. Indeed, some errors and outliers may occur precisely *because* subjects prepare the prime-congruent response (in mostly congruent blocks) or the prime-incongruent response (in mostly incongruent blocks), even though this response is incorrect in some trials. We did not wish to exclude such trials because they would capture exactly the control process of interest. We also excluded trials following "negative/absent RT" trials (see our earlier description of these trials) and trials wherein a malfunction produced an incorrect or absent prime RT. Just as we did not exclude trials based on the current probe response (see above), we did not exclude trials wherein the computer recorded the prime RT correctly but recorded a negative/absent probe RT. We reasoned that, in these trials, the recording of the negative/absent probe RT occurred *after* the measurement of preprobe force. Thus, there was no reason to exclude measures of preprobe force from these trials. Table 7 presents the conditional estimates of mean preprobe force (in cN) in Experiment 4.

Table 6

Mean Reaction Times and Mean Error Rates (and Corresponding Standard Errors) in Experiment 4

		Reaction time		Error rate	
Item type	Trial type	MC	MI	MC	MI
Inducer	Congruent	304 (6)	344 (6)	2.1 (0.4)	7.8 (1.7)
	Incongruent	344 (7)	305 (6)	6.1 (1.2)	2.0 (0.3)
	Cong effect	40	−39	4	−5.8
Diagnostic	Congruent	323 (7)	340 (6)	3.3 (0.5)	6.1 (0.9)
	Incongruent	334 (7)	321 (7)	4.2 (0.6)	2.9 (0.5)
	Cong effect	11	−19	0.9	−3.2

Note. Each parenthetical value indicates the standard error of the condition mean across participants. MC = mostly congruent blocks; MI = mostly incongruent blocks; Cong effect = congruency effect.

Table 7

Mean Preprobe Force in Centinewtons (and Corresponding Standard Errors) in Experiment 4

Item type	Response key	MC	MI
Inducer	Prime-congruent	15.55 (1.05)	13.91 (1.01)
	Prime-incongruent	13.07 (0.98)	12.69 (0.95)
	Difference	2.48	1.22
Diagnostic	Prime-congruent	16.23 (0.95)	15.49 (1.04)
	Prime-incongruent	13.50 (0.91)	13.19 (1.03)
	Difference	2.73	2.3

Note. Each parenthetical value indicates the standard error of the condition mean across participants. Difference = preprobe force on the prime-congruent key minus preprobe force on the prime-incongruent key. MC = mostly congruent blocks; MI = mostly incongruent blocks.

Transparency and Openness

These were the same as in the prior experiments. The preregistration, task scripts, data analysis scripts, and raw data are available on the OSF (https://osf.io/5nw64/).

Results

Inducer Items

Mean Probe RT. There was a significant interaction between block type and trial type, $F(1, 47) = 171.76$, $p < .001$, $\eta_p^2 = 0.79$, $\mathrm{BF_I} = 4.619 \times 10^{21}$ (Figure 7a). As expected, the congruency effect was larger in mostly congruent blocks, 40 ms; $F(1, 47) = 60.18$, $p < .001$, $\eta_p^2 = 0.56$, $\mathrm{BF_I} = 7.578 \times 10^6$, than in mostly incongruent blocks, −39 ms; $F(1, 47) = 38.63$, $p < .001$, $\eta_p^2 = 0.45$, $\mathrm{BF_I} = 76911.15$. No other effects were significant.

Mean Probe ER. There was a significant interaction between block type and trial type, $F(1, 47) = 29.36$, $p < .001$, $\eta_p^2 = 0.39$, $\mathrm{BF_I} = 376257.73$. As in the mean RT data, the congruency effect was larger in mostly congruent blocks, 4.0%; $F(1, 47) = 9.39$, $p = .004$, $\eta_p^2 = 0.17$, $\mathrm{BF_I} = 27.89$, than in mostly incongruent blocks, −5.8%; $F(1, 47) = 12.71$, $p < .001$, $\eta_p^2 = 0.21$, $\mathrm{BF_I} = 65.41$. No other effects were significant.

Mean Preprobe Force. There were three significant effects. First, there was a main effect of block type, $F(1, 47) = 4.63$, $p = .036$, $\eta_p^2 = 0.092$, $\mathrm{BF_I} = 2.12$: Mean preprobe force was greater in mostly congruent blocks (14.31 cN) than in mostly incongruent blocks (13.30 cN). Second, there was a main effect of response key, $F(1, 47) = 24.72$, $p < .001$, $\eta_p^2 = 0.35$, $\mathrm{BF_I} = 2260.98$: Mean preprobe force was greater on the prime-congruent key (14.73 cN) than on the prime-incongruent key (12.88 cN). Third, there was an interaction between block type and response key, $F(1, 47) = 25.04$, $p < .001$, $\eta_p^2 = 0.35$, $\mathrm{BF_I} = 896.92$ (Figure 8).

Figures 8a–8b plot analog response force across time, starting at prime onset, on the prime-congruent and prime-incongruent keys, separately for the mostly congruent (Figure 8a) and mostly incongruent (Figure 8b) blocks. The peak in the dotted line, representing the prime-congruent key, corresponds to the (correct) response made to the prime. The analyses reported here focus on the interval between the two vertical solid lines on the right side of each plot.

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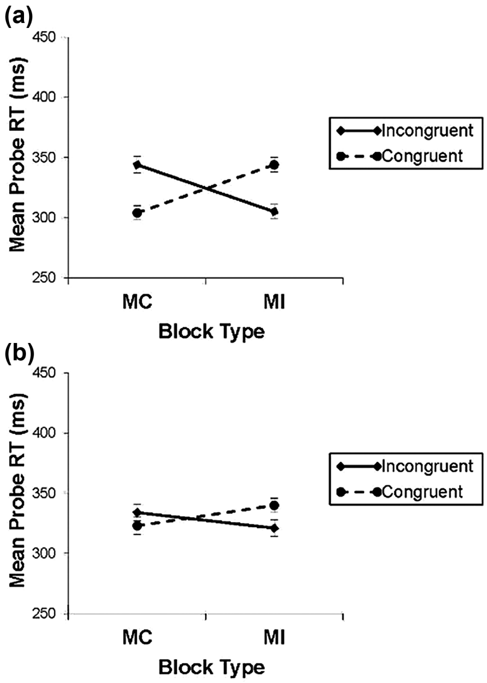
[6] See the Appendix for plots of mean force across the entire 3,000-ms duration of each trial.

Figure 7

Proportion Congruency Effects in Experiment 4



Note. Mean RT as a function of trial type (congruent, incongruent) and block type (MC = mostly congruent, MI = mostly incongruent) plotted separately for (a) inducer items and (b) diagnostic items. Positive and negative error bars indicate one standard error of the conditional mean across participants. RT = response time.

As shown in Figure 8c, mean force 0–200 ms before probe onset was always greater on the prime-congruent key than on the prime-incongruent key. Critically, the interaction indicates that this difference was larger in mostly congruent blocks, 2.48 cN; $F(1, 47) = 40.99$, $p < .001$, $\eta_p^2 = 0.47$, $\mathrm{BF_I} = 133956.61$; Figure 8c, left, than in mostly incongruent blocks, 1.21 cN; $F(1, 47) = 9.41$, $p = .004$, $\eta_p^2 = 0.17$, $\mathrm{BF_I} = 9.35$; Figure 8c, right.

Diagnostic Items

Mean Probe RT. There was a significant interaction between block type and trial type, $F(1, 47) = 65.05$, $p < .001$, $\eta_p^2 = 0.58$, $\mathrm{BF_I} = 3.050 \times 10^8$ (Figure 7b). As expected, the congruency effect was larger in mostly congruent blocks, 11 ms; $F(1, 47) = 6.92$, $p = .011$, $\eta_p^2 = 0.13$, $\mathrm{BF_I} = 3.93$, than in mostly incongruent blocks, −19 ms; $F(1, 47) = 14.32$, $p < .001$, $\eta_p^2 = 0.23$, $\mathrm{BF_I} = 53.77$. No other effects were significant.

Mean Probe ER. There was a significant interaction between block type and trial type, $F(1, 47) = 30.05$, $p < .001$, $\eta_p^2 = 0.39$, $\mathrm{BF_I} = 17887.93$. As in the mean RT data, the congruency effect was larger in mostly congruent blocks, 0.9%; $F(1, 47) = 2.43$, $p = .13$, $\eta_p^2 = 0.05$, $\mathrm{BF_I} = 0.61$, than in mostly incongruent blocks, −3.2%; $F(1, 47) = 18.70$, $p < .001$, $\eta_p^2 = 0.29$, $\mathrm{BF_I} = 211.96$. No other effects were significant.

Mean Preprobe Force. There were two significant effects. First, there was a main effect of response key, $F(1, 47) = 42.92$, $p < .001$, $\eta_p^2 = 0.48$, $\mathrm{BF_I} = 221078.81$: Mean preprobe force was greater on the prime-congruent key (14.87 cN) than on the prime-incongruent key (14.34 cN). Second, there was a Block Type × Response Key interaction, $F(1, 47) = 4.44$, $p = .041$, $\eta_p^2 = 0.09$, $\mathrm{BF_I} = 1.04$ (Figure 9).

Figures 9a–9b plot analog response force across time, starting at prime onset, on the prime-congruent and prime-incongruent keys, separately for the mostly congruent (Figure 9a) and mostly incongruent (Figure 9b) blocks. Again, the peak in the dotted line, representing the prime-congruent key, corresponds to the (correct) response made to the prime, and the present analyses focus on the interval between the two vertical solid lines on the right side of each plot. As shown in Figure 9c, mean force 0–200 ms before probe onset was always greater on the prime-congruent (vs. prime-incongruent) key. Critically, however, the interaction indicates that this effect was larger in mostly congruent blocks, 2.78 cN; $F(1, 47) = 54.00$, $p < .001$, $\eta_p^2 = 0.54$, $\mathrm{BF_I} = 2.799 \times 10^6$; Figure 9c, left, than in mostly incongruent blocks, 2.30 cN; $F(1, 47) = 29.75$, $p < .001$, $\eta_p^2 = 0.39$, $\mathrm{BF_I} = 6976.36$; Figure 9c, right.

Discussion

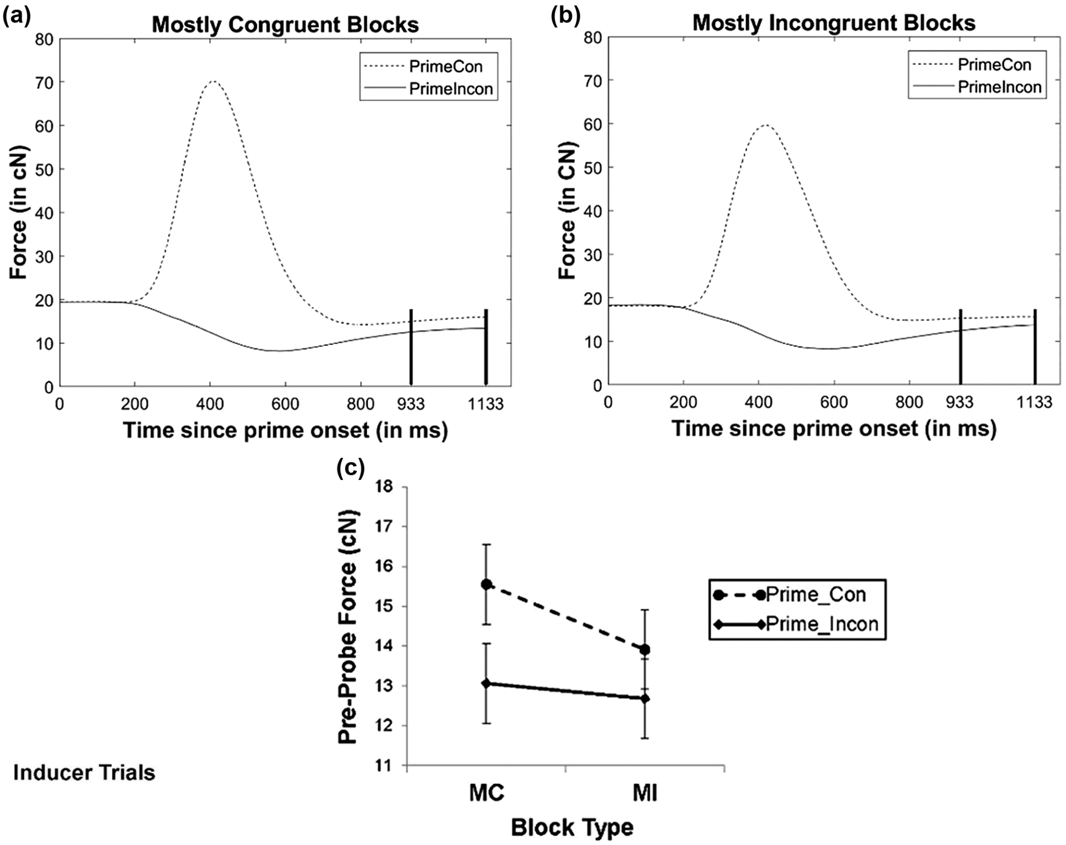
In Experiment 4, we used force-sensitive keyboards to seek evidence for the response modulation account of the PCE at long SOAs that the congruency switch account cannot explain. We observed greater preprobe force on the prime-congruent (vs. the prime-incongruent) key. Critically, this main effect was larger in mostly congruent blocks than in mostly incongruent blocks. This interaction between block type and response key is consistent with the response modulation account. Here, control processes combine information about block-wide congruency statistics (i.e., mostly congruent or mostly incongruent) with the identity of the prime (e.g., left arrow) to prepare a congruent (e.g., left) or incongruent (e.g., right) response to the probe *before* the probe appears. In contrast, this interaction between block type and response key neither supports nor challenges the congruency switch account. As congruency switch costs arise only *after* the probe appears (i.e., only after the current trial's congruency is established), this account does not predict systematic changes in *preprobe* force. For this reason, our findings in Experiment 4 provide evidence for the response modulation account of the PCE at long SOAs that the congruency switch account cannot explain. Of course, the present findings do not rule out a contribution of congruency switch costs to the PCE *after* the probe appears.

We note that the simple effects of the interaction between block type and response key matched our initial expectations only in mostly congruent blocks. In these blocks, faster RTs in congruent (vs. incongruent) trials were preceded by greater preprobe force on the prime-congruent (vs. prime-incongruent) key. This outcome suggests advance preparation of the prime-congruent response in mostly congruent blocks. In mostly incongruent blocks, however, faster RTs in incongruent (vs. congruent) trials were also preceded by greater preprobe force on the prime-congruent (vs. prime-incongruent) key. The size of this effect was smaller than in mostly congruent blocks, which led to the significant interaction that we observed. Contrary to our expectations, however, this outcome appears to suggest advance preparation of the prime-congruent response in mostly incongruent blocks, rather than of the prime-incongruent response.

It is important to remember, however, that participants pressed the prime-congruent key when responding to the initial prime in each trial. If participants rested their finger on this key after responding to the prime, one would expect greater preprobe force on the prime-congruent

Figure 8

Mean Force in Inducer Trials Time-Locked to the Onset of the Prime and Averaged Across Participants



Note. The two upper panels plot mean force on the prime-congruent (PrimeCon) and prime-incongruent (PrimeIncon) response keys in centinewtons (cN), separately for (a) mostly congruent blocks and (b) mostly incongruent blocks. The two vertical lines on the right side of each of these plots highlight the interval from 933 to 1,133 ms after prime onset, which corresponds to 0–200 ms before probe onset and provides a measure of preprobe force. (c) Mean preprobe force as a function of response key (prime-congruent, prime-incongruent) and block type (MC = mostly congruent, MI = mostly incongruent). Although mean preprobe force was always greater on the prime-congruent key than on the prime-incongruent key, this difference was larger in mostly congruent blocks than in mostly incongruent blocks.

(vs. prime-incongruent) key in both mostly congruent and mostly incongruent blocks—that is, a main effect of response key on preprobe force (prime-congruent > prime-incongruent), which we did observe for both inducer and diagnostic items. Thus, in our view, the interaction between block type and response key still supports the response modulation account of the PCE. Even in the presence of the main effect of response key above (i.e., prime-congruent > prime-incongruent), this interaction shows a relative shift in response activation toward (a) the prime-congruent key in mostly congruent blocks and/or (b) the prime-incongruent key in mostly incongruent blocks. This shift confirms the predictions of the response modulation account.

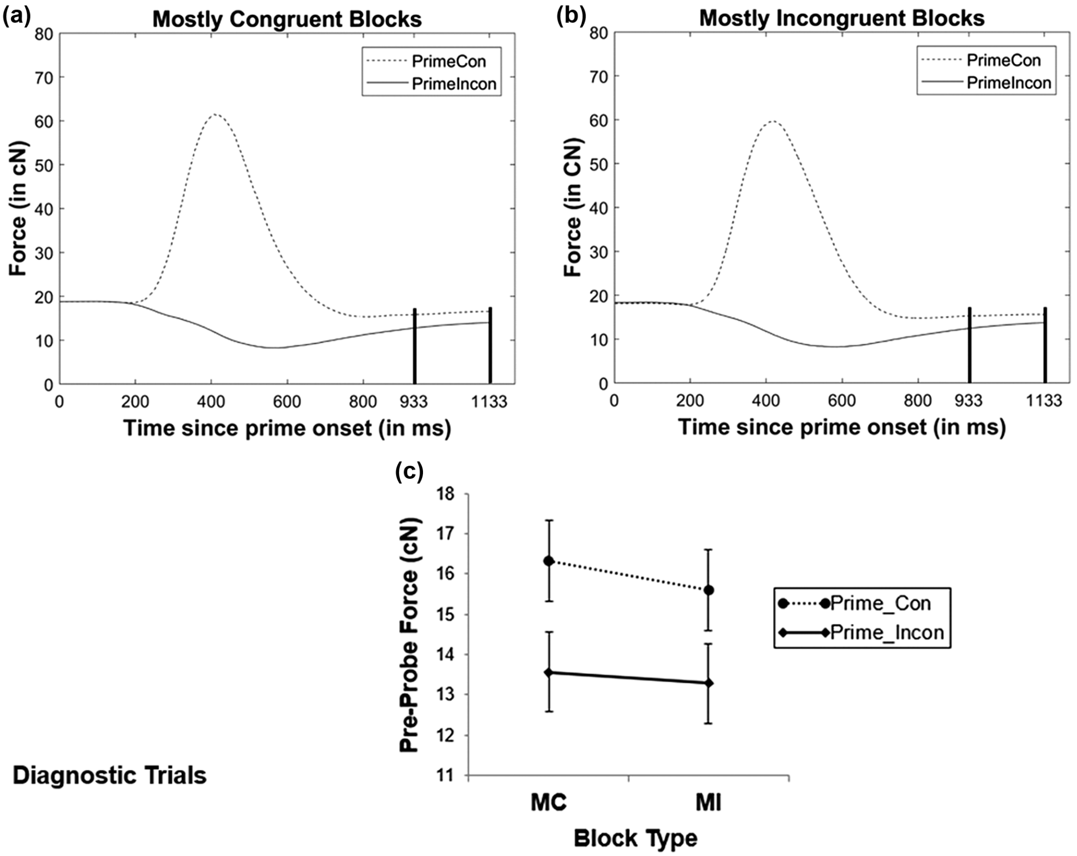
Exploratory Analyses

One may wonder about the potential influence of orthogonal compatibility effects (Cho & Proctor, 2003; Loetscher et al., 2010) on the PCEs that we have observed. Such compatibility effects occur because leftward locations are more strongly associated with downward locations than with upward locations while the reverse holds for rightward locations. Given such effects, attentional adaptations to Left arrow primes might affect not only Left arrow probes (due to their similarity), but also Down arrow probes due to strengthened associations between leftward and downward locations. More generally, experiencing a compatible "Left arrow prime–Down arrow probe" or "Right arrow prime–Up arrow probe" transition in consecutive trials may influence congruency effects and/or PCEs differently than experiencing an incompatible "Left arrow prime–Up arrow probe" or "Right arrow prime–Down arrow probe" transition.

To investigate the possible influences of such *transitional orthogonal compatibility*, we conducted exploratory analyses of the data from diagnostic trials in Experiments 1–4. Here, we entered transitional compatibility as a factor in the repeated-measures ANOVA. In transitionally compatible trials, a Left arrow prime in trial $n - 1$ preceded a Down arrow probe in trial n or a Right arrow prime in trial $n - 1$ preceded an Up arrow probe in trial n. In transitionally incompatible trials, a Left arrow prime in trial $n - 1$ preceded an Up arrow probe in trial n or a Right arrow prime in trial $n - 1$ preceded a Down arrow probe in trial n.

Figure 9

Mean Force in Diagnostic Trials Time-Locked to the Onset of the Prime and Averaged Across Participants



Note. The two upper panels plot mean force on the prime-congruent (PrimeCon) and prime-incongruent (PrimeIncon) response keys in centinewtons (cN), separately for (a) mostly congruent blocks and (b) mostly incongruent blocks. The two vertical lines on the right side of each of these plots highlight the interval from 933 to 1,133 ms after prime onset, which corresponds to 0–200 ms before probe onset and provides a measure of preprobe force. (c) Mean preprobe force as a function of response key (prime-congruent, prime-incongruent) and block type (MC = mostly congruent, MI = mostly incongruent). Although mean preprobe force was always greater on the prime-congruent key than on the prime-incongruent key, this difference was larger in mostly congruent blocks than in mostly incongruent blocks.

For Experiments 1 and 2, which involved only the standard prime-probe task, the other factors were block type (mostly congruent vs. mostly incongruent), SOA (0 ms vs. 933 ms), and trial type (congruent, incongruent). For Experiments 3 and 4, wherein we focused solely on the modified prime-probe task, the other factors in the ANOVA were block type (mostly congruent vs. mostly incongruent) and trial type (congruent, incongruent). The number of trials per condition in this analysis was necessarily lower than in the main analysis. Indeed, in our random trial sequences, only 50% of the diagnostic trials should follow inducer trials. Furthermore, only half of these diagnostic trials should be transitionally compatible (25% of all diagnostic trials) while the other half should be transitionally incompatible (25% of all diagnostic trials).

The results were as follows. In Experiment 1, there were no main effects or interactions involving transitional compatibility in mean RT (all $p > .09$) or mean ER (all $p > .14$). In Experiment 2, there were also no main effects or interactions involving transitional compatibility in mean RT (all $p > .15$) or mean ER (all $p > .14$). In Experiment 3, wherein we focused solely on the modified prime-probe task, we observed a three-way interaction among block type, trial type, and transitional compatibility, $F(1, 47) = 4.70$, $p = .035$, $\eta_p^2 = 0.09$, $\mathrm{BF_I} = 9.0$, in mean RT, because the PCE was larger in transitionally compatible trials (53 ms) than in transitionally incompatible trials (29 ms). No effects or interactions involving transitional compatibility were significant in mean ER (all $p > .25$). Finally, in Experiment 4, which involved only the modified prime-probe task, there were no significant main effects or interactions involving transitional compatibility in either mean RT (all $p > .16$) or mean ER (all $p > .06$).

In short, our findings in Experiments 1–4 suggest that transitional compatibility exerts little, if any, influence on congruency effects or the PCE. The only exception comes from Experiment 3, which revealed an influence of transitional compatibility on the PCE in the modified prime-probe task. Experiment 4, however, did not replicate this effect. It is worth noting, however, that there were more trials per condition in the modified prime-probe task of Experiment 4, which involved only the modified prime-probe task, than in the modified prime-probe task of Experiment 3, which involved both the standard and modified prime-probe tasks. Thus, although Experiment 4 did not replicate the effect produced by Experiment 3, statistical power was likely higher in Experiment 4. For this reason, Experiment 4 may provide a more accurate estimate of the influence of transitional compatibility on the PCE in the modified prime-probe task. Whatever the source of the inconsistency between Experiments 3 and 4, taken together our findings from Experiments 1–4 suggest that transitional compatibility exerts little, if any, influence on the PCE.

General Discussion

We conducted four experiments to investigate the response modulation and attentional shift accounts of the PCE in the standard and modified prime-probe tasks. More specifically, we investigated whether a modulation of response activation contributes to the PCE by determining whether—in some situations—the PCE varies in ways that the response modulation account can explain but the attentional shift account cannot explain. Although the present findings do not differentiate between the response modulation and attentional shift accounts at short prime-probe SOAs in the standard prime-probe task, they indicate that only the response modulation account can explain PCEs at long SOAs in each of these tasks. This novel outcome supports the response modulation account of the PCE at long SOAs. It also shows that the associated control processes contribute to cognition in ways that are broader than minimizing distraction from irrelevant stimuli. Finally, this outcome serves to integrate the largely distinct literatures on the CSE and PCE by showing that the response modulation account can explain cognitive control at long prime-probe SOAs not only at short timescales (i.e., the CSE) but also at long timescales (i.e., the PCE).

Implications for the Response Modulation Account

The present findings support the response modulation account of the PCE at long prime-probe SOAs. First, in Experiments 2–4, we observed PCEs without overall congruency (i.e., conflict) effects in both the standard and modified prime-probe tasks. Further, these PCEs were associated with negative congruency effects in mostly incongruent blocks. As we described earlier, these findings are more consistent with the response modulation account than with the attentional shift account. For example, shifting attention away from the distractor could eliminate—but not reverse—the congruency effect. Second, in Experiment 4, we observed a PCE-like effect in response force before the probe appeared in the modified prime-probe task. As we indicated earlier, this outcome fits with the response modulation account of the PCE but not with the congruency switch account wherein congruency switch costs occur *after* the probe appears. These findings suggest that similar control mechanisms operate at long (PCE) and short (CSE) timescales in the prime-probe task. Indeed, our findings at long SOAs suggest that control processes produce the PCE by modulating the response cued by the distractor, rather than by shifting attention toward the target. This outcome mirrors analogous findings from the literature on the confound-minimized CSE and, therefore, serves to integrate the PCE and CSE literatures.

Although our findings suggest a common *target* of control (i.e., prime-related response activation) at long (PCE) and short (CSE) timescales, they suggest different *triggers* of control at these timescales. Specifically, in Experiment 3, we observed equivalent PCEs in the modified and standard prime-probe tasks, rather than a larger PCE in the modified prime-probe task as in the case of the CSE (Grant & Weissman, 2019, 2023). As we described earlier, this outcome suggests that block-wide congruency statistics (i.e., mostly congruent vs. mostly incongruent) trigger control processes underlying the PCE (Bugg & Chanani, 2011; Logan & Zbrodoff, 1979). In contrast, prior findings suggest that retrieving a memory of the *previous trial* is what triggers control processes underlying the CSE (Egner, 2014; Spapé & Hommel, 2008; Weissman et al., 2016). The view that the CSE and the PCE result from different triggers of control at short and long timescales, respectively, is consistent with data showing that the sizes of the CSE and the PCE can vary somewhat independently of each other (Torres-Quesada et al., 2013, 2014).

Given our findings suggesting different triggers of control for the CSE and the PCE, one may wonder whether memory triggers the PCE differently than it triggers the CSE. To address this issue, we begin by describing an emerging view wherein the cognitive system forms an episodic memory of each trial, or “event file” (Hommel, 1998), that stores trial-specific features at various levels of abstraction (Egner, 2014; Spapé & Hommel, 2008; Weissman et al., 2016). These include concrete stimulus and response features such as “red” and “left keypress,” categorical features such as “congruent” and “incongruent,” and abstract features such as task sets (e.g., “identify which color appears via one of four keypresses”) and control parameters (e.g., “focus strongly on the relevant color” or “inhibit the response associated with the irrelevant word”). In this view, repeating a feature (e.g., “red”) from the previous trial retrieves the previous trial’s event file, which reactivates, or primes, other features from that same trial (e.g., “left keypress”). In terms of the CSE, repeating an abstract feature (e.g., the task) can trigger the retrieval of the previous trial’s congruency-related control parameters (e.g., “inhibit the response cued by the distractor”) even when no concrete stimulus or response features repeat in consecutive trials. Retrieving this information facilitates performance when congruency repeats (vs. alternates) and thereby produces a CSE.

To explain the confound-minimized PCE, Egner (2014) proposed that a temporally extended event file, or “episode file,” stores the temporal context in which a trial occurs. The temporal context includes any temporally extended contingencies, control states, and task sets that are active during a trial (e.g., a contingency such as “the trials in this block are mostly incongruent”). In this view, an episode file is retrieved or maintained as long as there is no change to the temporal context (e.g., to the relative proportions of congruent and incongruent trials in a block). Such retrieval/maintenance can reactivate, or prime, any associated features from the same episode file including abstract control states (e.g., “inhibit the response associated with the distractor”) for an extended period of time (e.g., an entire block of trials). Thus, memory triggers the control processes underlying the confound-minimized PCE, albeit in a somewhat different way than it triggers the control processes underlying the confound-minimized CSE.

The view that memory triggers the processes that give rise to the PCE suggests the possibility that priming contributes to the PCEs we have observed. In the simplest priming account, participants learn (and store in event or episode files) associations between specific prime arrows (e.g., left and right arrows) and specific probe responses (e.g., left and right keypresses). Next, when a given prime arrow appears, participants retrieve (probably implicitly) the likely upcoming probe response (e.g., a left arrow prime triggers the retrieval of a right keypress in mostly incongruent blocks). This account can explain the PCEs that we observed for inducer (i.e., left and right arrow) items. Indeed, within each block, each inducer prime arrow (e.g., each left arrow) was followed more often by one probe response (e.g., right keypress) than by the other probe response (e.g., left keypress; of course, the specific probe response that followed each prime arrow more often varied across mostly congruent and mostly incongruent blocks). This account, however, cannot explain the PCEs that we observed for diagnostic (i.e., up and down) items, because each diagnostic prime arrow was followed equally often by up and down probe responses. One could posit a more abstract priming account, though (Hommel, 1998), wherein participants learn and later retrieve from event or episode files (again, probably implicitly) an abstract "rule" that prime arrows on the whole predict same direction targets in mostly congruent blocks and different direction targets in mostly incongruent blocks. This abstract priming account can explain the PCEs that we observed for both inducer and diagnostic items. We note that this account is functionally similar to the response modulation account but is phrased in terms of "priming" rather than in terms of "cognitive control." Future studies could explore this potentially important distinction.

Implications for the Attentional Shift Account

The present findings show that a conflict-triggered shift of attention toward the target and away from the distractor in mostly incongruent (vs. mostly congruent) blocks cannot fully explain the PCE in the prime-probe task. In fact, our findings provide no evidence for an attentional shift that the response modulation account cannot also explain. This outcome does not rule out the possibility that an attentional shift also contributes to the PCE, however, which we discuss next.

As we have described throughout the article, our findings at short prime-probe SOAs are consistent with both the response modulation and attentional shift accounts. First, consider the larger PCE at the 166-ms (vs. 0 ms) SOA in Experiment 1. The response modulation account can explain this finding because the distractor received a larger "head start" in stimulus–response translation over the target at the 166-ms SOA. The attentional shift account can also explain this finding, however, as the overall congruency (i.e., conflict) effect was larger at the 166-ms SOA. Second, consider the nonsignificant PCE at the 0-ms SOA. The response modulation account can explain this finding if the distractor's "head start" in stimulus–response translation was not sufficient for control processes to modulate the response cued by the distractor before participants responded to the target. The attentional shift account can also explain this finding, however, if one assumes that the overall congruency effect was too small to trigger control.

Third, consider the larger PCE at the 166-ms (vs. 933 ms) SOA in Experiment 2. This finding might reflect a stronger shift of attention toward the target at the 166-ms SOA because the overall congruency effect was larger at the 166-ms SOA. However, it might also reflect a stronger modulation of response activation if less effort is required to sustain control across a 166-ms (vs. 933 ms) SOA (Shenhav et al., 2013). Another possible interpretation is that an attentional shift *and* a modulation of response activation jointly produce the larger PCE at the 166-ms SOA. Finally, this finding could indicate that an attentional shift occurs only at the 166-ms SOA while a modulation of response activation occurs only at the 933-ms SOA.

These findings suggest that complementary approaches may be necessary to differentiate between the attentional shift and response modulation accounts of the PCE at *short* SOAs. One such approach could involve computational modeling. For example, consider the diffusion model for conflict tasks, which analyzes within-subject RT distributions to differentiate the influence of control on (a) task-irrelevant information versus (b) task-relevant information (Koob et al., 2023). Such a model could potentially indicate whether the PCE reflects a shift of attention toward the target, a modulation of the response cued by the distractor, or both. In line with the second possibility, fitting this model to data from the Flanker and Simon tasks suggests that the CSEs in these tasks reflect a suppression of task-irrelevant (i.e., distractor-related) information rather than an enhancement of task-relevant (i.e., target-related) information (Koob et al., 2023). Future modeling studies could aim to investigate whether such findings generalize to the PCE and whether suppressing task-irrelevant information includes inhibiting the response cued by the distractor more in mostly incongruent (vs. mostly congruent) blocks (Ulrich et al., 2015).

Broader Implications

The present findings show for the first time that a cognitive control mechanism can produce a confound-minimized PCE even when a distractor appears considerably before a target. This type of distraction is incredibly common in everyday tasks (e.g., imagine a driver who receives a text message shortly before a traffic light turns red), but surprisingly uncommon in the laboratory tasks (e.g., the Stroop, Simon, and Flanker tasks) that researchers typically employ to measure the PCE. Indeed, distractors and targets usually appear simultaneously in these tasks. For this reason, the present findings may provide a more accurate picture of the control processes that operate when distractors precede targets in real-world settings.

The present findings also show that the control processes underlying the PCE in the prime-probe task make a broader contribution to cognition than minimizing distraction from irrelevant stimuli. More specifically, we found that PCEs appear not only in the standard prime-probe task, wherein the prime serves as a distractor, but also in the modified prime-probe task, wherein the prime serves as an initial target. This outcome suggests that the control processes underlying the PCE in the prime-probe task are not specific to coping with distraction. As described earlier, they may play a role in learning abstract relationships between stimuli and/or responses (e.g., similar vs. dissimilar; Weissman et al., 2020).

The present findings suggest the possibility that a modulation of response activation may also contribute to the PCE in other distractor-interference tasks. As we described earlier, findings from the diffusion model for conflict tasks suggest that the CSE in the Flanker and Simon tasks is more consistent with a suppression of task-irrelevant (i.e., distractor-related) information than with enhanced processing of task-relevant (i.e., target-related) information (Koob et al., 2023). If future studies show that suppressing task-irrelevant information in this modeling framework includes inhibiting the response cued by the distractor, then future studies that make use of this modeling framework could be helpful for determining whether a modulation of the response cued by the distractor contributes to the PCE in a wide variety of distractor-interference tasks.

Finally, the present findings indicate that force-sensitive keyboards can be extremely useful for investigating the predictions of the response modulation account. More specifically, our findings from such keyboards in Experiment 4 allowed us to observe effects that the response modulation can explain but the congruency switch account cannot explain (i.e., systematic changes in response activation prior to target stimulus onset). To our knowledge, our study is the first to employ such keyboards to investigate the response modulation account of the PCE. Since such keyboards allow one to track response activation for multiple fingers on the same hand with relatively high temporal resolution, they may also be useful for investigating the role of advance response preparation in producing other interesting phenomena. For example, we have recently used such keyboards to investigate the role of response preparation in producing the CSE (Weissman, 2019) and contingency learning effects (Weissman & Schmidt, 2024).

Limitations

The present study has three straightforward limitations that researchers should consider. First, as we described earlier, our findings do not differentiate between the response modulation and attentional shift accounts at short prime-probe SOAs. Consequently, additional studies will be necessary to make this distinction. Second, it remains unclear whether the present findings generalize to more typical distractor-interference tasks wherein distractors and targets (a) appear simultaneously rather than sequentially and (b) are perceptually distinct (e.g., colors vs. words in the Stroop task) rather than similar (e.g., small arrows vs. large arrows in the prime-probe task). Even if the present findings do not generalize to such tasks, however, they are still relevant because, for example, distractors often occur before targets in everyday life (e.g., as when a smartphone beeps a second before a colleague or friend tells us something important). Third, our findings in Experiment 4 do not rule out the possibility that congruency switch costs contribute to the PCE after the target appears. Even if this is the case, however, the present findings still clearly indicate that a modulation of response activation occurs prior to target onset, which is more consistent with the response modulation account than with the congruency switch account.

Given prior data indicating that participants expect stimulus/response repetitions at short (nonzero) SOAs and stimulus/response alternations at long SOAs (M. Jones et al., 2013; Soetens, 1998), one may also wonder whether such expectations influenced the PCE in our study. This appears unlikely as, at any given SOA, such biases (e.g., to repeat a previous response) should be similar in mostly congruent and mostly incongruent blocks. Thus, any difference in the size of the congruency effect that appears in these different block types (i.e., any PCE) must reflect processes over and above those responsible for simple stimulus/response repetition versus alternation biases.

One may also wonder whether, relative to 0-ms SOAs, there are abstract biases to alternate trial congruency at long SOAs and to repeat trial congruency at short (nonzero) SOAs. Such biases should reduce the degree to which the cognitive system prepares for a congruency repetition at long SOAs relative to both short SOAs and 0-ms SOAs. Thus, such biases should produce smaller PCEs at long SOAs than at either short SOAs or 0-ms SOAs. Two findings argue against this possibility. First, we observed a significant PCE for the diagnostic trials at a long 933-ms SOA in Experiment 2 even though we did not observe a PCE at the 0-ms SOA in Experiment 1. Second, in a recent, unpublished study ($N = 40$) that involved the same task as in the present study with different SOA combinations, we observed a significantly larger PCE for the diagnostic trials at a long 633-ms SOA than at a 0-ms SOA. These findings suggest that biases to alternate congruency at long SOAs and to repeat trial congruency at short SOAs are unlikely to explain our findings.

It is also important to discuss the possibility that the present tasks encourage the use of a response modulation mechanism to produce a PCE (rather than an attentional shift mechanism) because they make use of a restricted stimulus set wherein each prime is associated with one congruent probe and one incongruent probe. This task design may allow participants to use the primes to predict probe responses more easily than designs that make use of less restrictive stimulus sets. We cannot rule out this possibility, but it appears unlikely that our findings are limited to this task design for the following reason. Even in tasks that pair each inducer prime with more than one inducer probe response in mostly incongruent blocks, a more general response modulation process remains possible: Control processes can inhibit the response that is cued by the prime (Ridderinkhof, 2002). Control processes may also enhance the response that the prime cues in mostly congruent blocks because each inducer prime is highly predictive of a single inducer probe response (note that such high predictability in mostly congruent blocks is also present in other tasks such as the Stroop, Flanker, and Simon tasks). Thus, a confound-minimized PCE in such tasks may still (at least partly) reflect control processes that modulate response activation differently in mostly incongruent blocks (e.g., inhibit the response cued by the prime) than in mostly congruent blocks (e.g., enhance the response cued by the prime).

Whether or not different study designs encourage the use of different control processes is an interesting (yet understudied) topic in its own right. Consequently, follow-up studies could investigate whether support for a response modulation account of the PCE appears even when each prime is associated with more than one probe in mostly incongruent blocks. The goal of the present research, however, was simply to determine whether a response modulation mechanism *ever* contributes to the confound-minimized PCE. Our findings clearly confirm this hypothesis.

Conclusion

Although the present findings do not differentiate between the response modulation and attentional shift accounts of the PCE in the prime-probe task at relatively short prime-probe SOAs, they clearly indicate a contribution of control processes that modulate response activation to the PCE at relatively long prime-probe SOAs. The present findings also indicate that the control processes underlying the PCE at long prime-probe SOAs contribute to cognition in ways that extend beyond minimizing distraction from irrelevant stimuli. Finally, the present findings suggest different triggers for the control processes that underlie the CSE and the PCE at long prime-probe SOAs while revealing that prime-related response activation serves as a common target of these control processes. Future work investigating the nature of the CSE and the PCE may reveal additional novel insights into how cognitive control processes cope with distraction from irrelevant stimuli at both short (e.g., CSE) and long (e.g., PCE) timescales.

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Appendix

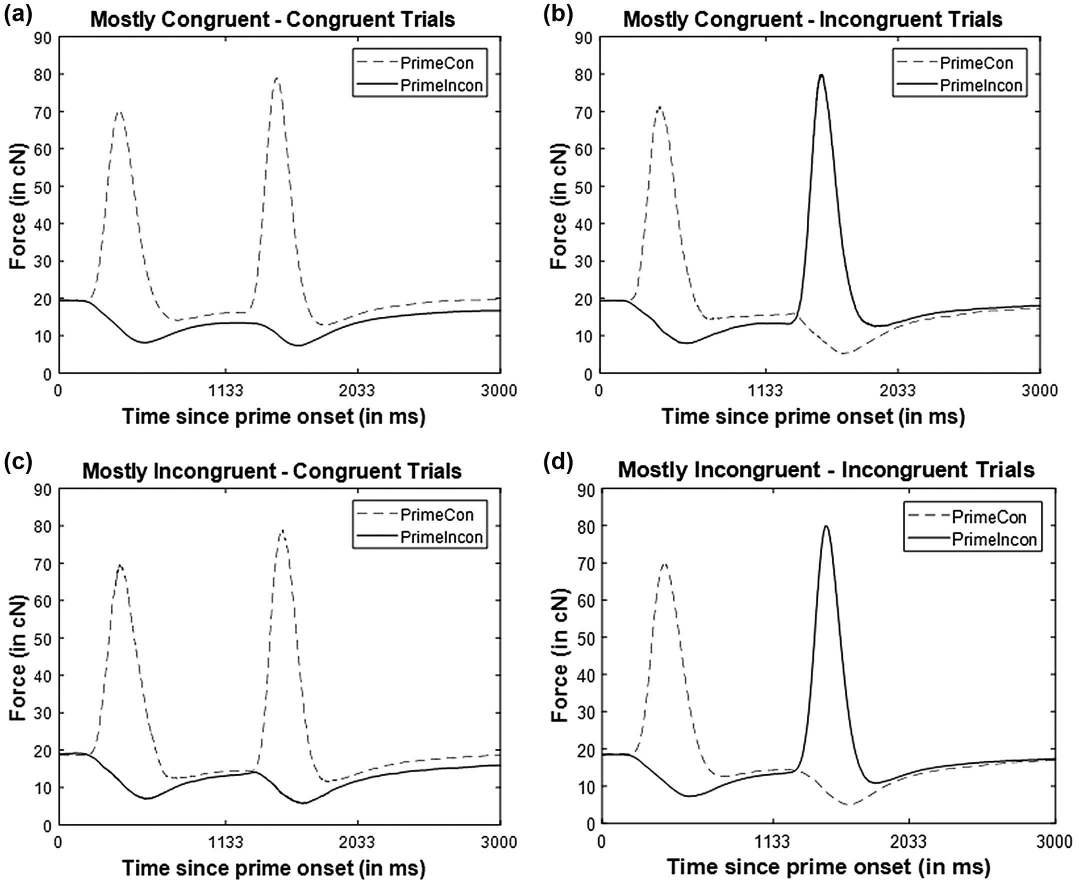
Force Across the Entire 3,000-ms Trial Duration

We have no specific hypotheses regarding force during the target (i.e., probe) portion of each trial. Nonetheless, we deem it useful to provide the force curves for the entire 3,000-ms trial duration in this Appendix. Our aim is to provide greater context for interpreting our findings in the main text and to stimulate future ideas and hypotheses. We generated the figures below using only those trials wherein participants responded correctly to both the prime and the probe.

For the inducer items (Figure A1), peak force after the probe onsets at 1,133 ms is higher on the prime-congruent key in congruent trials but higher on the probe-incongruent key in incongruent trials. These effects occur because the probe requires the response cued by the prime (the prime-congruent response) in congruent trials but requires the response opposite to the one cued by the prime (the prime-incongruent response) in incongruent trials. In other words, these effects stem from our task design. Note also that

Figure A1

Mean Force in Inducer Trials Averaged Across Participants



Note. Mean force in inducer trials time-locked to prime onset and averaged across participants in each of the four combinations of block type (mostly congruent, mostly incongruent) and trial type (congruent, incongruent). These include (a) mostly congruent–congruent trials, (b) mostly congruent–incongruent trials, (c) mostly incongruent–congruent trials, and (d) mostly incongruent–incongruent trials. The figure plots mean force on the prime-congruent (PrimeCon) and prime-incongruent (PrimeIncon) response keys in centinewtons (cN). The prime onsets at 0 ms and the probe onsets at 1,133 ms.

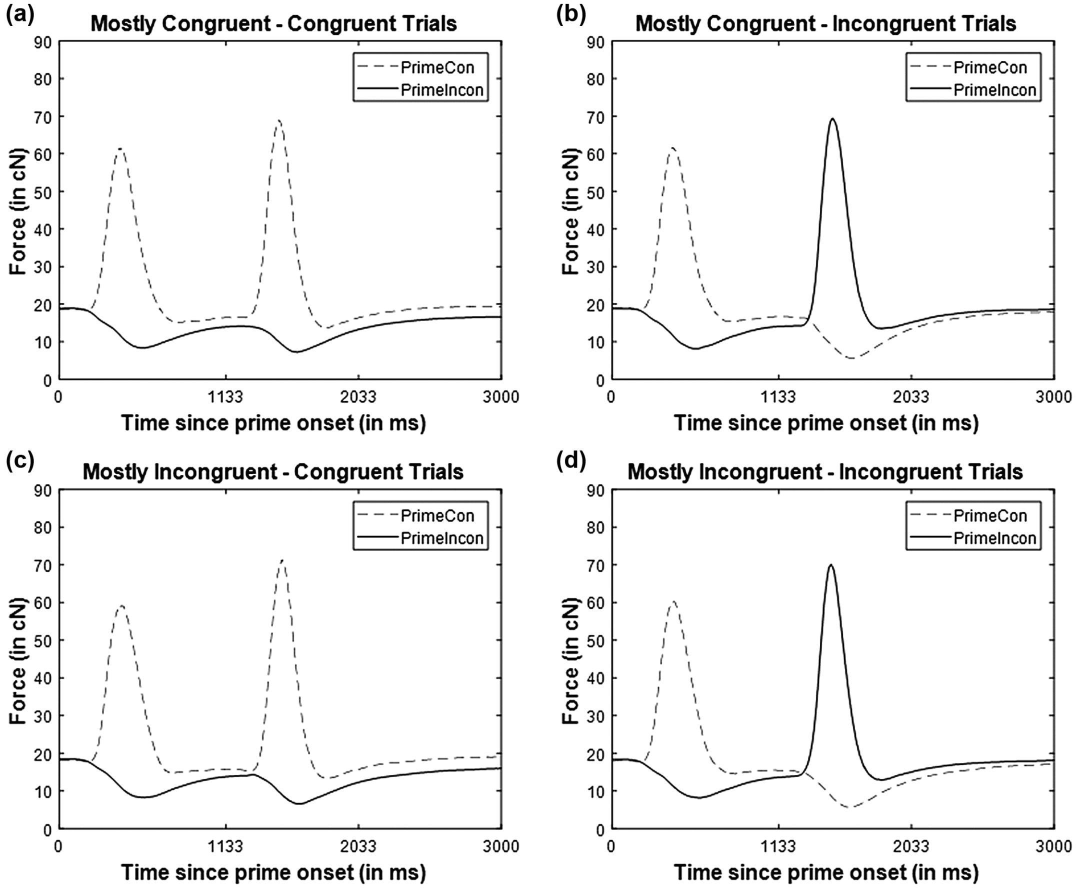
(*Appendix continues*)

overall force is higher 1867 ms after probe onset (3,000 ms on the *x*-axis) than 900 ms after probe onset (2033 ms on the *x*-axis). This shows that force continues to return to baseline (following its postresponse dip below baseline) well after participants respond to the probe.

Finally, note that force remains higher on the prime-congruent key than on the prime-incongruent key even 1867 ms after probe onset (3,000 ms on the *x*-axis) in congruent trials while there is a trend in the opposite direction in incongruent trials. This may indicate that participants rest their finger on the key they last pressed, as we described in the Discussion of Experiment 4. This does not, however, translate into higher baseline force for either response key at the beginning of each trial (e.g., 0–200 ms after prime onset), as the prime-congruent and prime-incongruent keys switch randomly across trials. For this reason, the prime-congruent key may start out with higher force than the prime-incongruent key in some trials (i.e., because the same—e.g., “Left”—key served as the prime-congruent key in the previous trial) but with lower force than the prime-incongruent key in other trials (i.e., because the opposite—e.g., “Right”—key served as the prime-congruent key in the previous trial), yielding no average difference in baseline force on these two keys. Consistent with this reasoning, the dashed (prime-congruent key) and solid (prime-incongruent key) force curves overlap 0–200 ms after prime onset, which corresponds to the first 200 ms of each trial (see also, the left side of Figure 8a–8b). Finally, we note that we observed similar patterns of force for the diagnostic items (Figure A2).

Figure A2

Mean Force in Diagnostic Trials Averaged Across Participants



Note. Mean force in diagnostic trials time-locked to prime onset and averaged across participants in each of the four combinations of block type (mostly congruent, mostly incongruent) and trial type (congruent, incongruent). These include (a) mostly congruent–congruent trials, (b) mostly congruent–incongruent trials, (c) mostly incongruent–congruent trials, and (d) mostly incongruent–incongruent trials. The figure plots mean force on the prime-congruent (PrimeCon) and prime-incongruent (PrimeIncon) response keys in centinewtons (cN). The prime onsets at 0 ms and the probe onsets at 1,133 ms.

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