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Determinants of Congruency Sequence Effects Without Learning and Memory Confounds

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A common finding in distracter interference (e.g., Flanker) tasks is that the difference in mean reaction time (RT) between incongruent and congruent trials—the congruency effect—is smaller when the previous trial was incongruent relative to congruent. Over the past 2 decades, 2 main accounts of this *congruency sequence effect* (CSE) have been proposed. One posits that the CSE indexes trial-by-trial adjustments of cognitive control, which are triggered by expectation, response conflict, negative affect, or response suppression. The other holds that the CSE indexes feature integration and/or contingency learning processes that are confounded with congruency sequence in most studies. In 3 online experiments involving over 450 participants, we observed CSEs without such confounds when 2 preconditions were met: (a) stimulus-response translation could be completed more rapidly for the distracter than for the target and (b) the distracter and target appeared at the same location. We also found that CSE magnitude did not vary consistently with the size of the congruency effect. These findings reveal that CSEs can be observed in the absence of feature integration and contingency learning confounds, but impose important new constraints on certain *cognitive control* accounts of this phenomenon.

Keywords: conflict adaptation, Gratton effect, sequential modulations, congruency sequence effect, Amazon's Mechanical Turk

The efficiency of selective attention is often measured with distracter interference tasks. In each trial of such tasks, participants are instructed to identify a relevant target while ignoring one or more irrelevant distracters. In the classic flanker task, for example, participants are often instructed to identify a relevant target letter at fixation that is flanked on the left and right sides by one or more copies of an irrelevant distracter letter (Eriksen & Eriksen, 1974). In congruent trials (e.g., HHH or SSS), the distracters are mapped to the same response as the target. In incongruent trials (e.g., SHS or HSH), the distracters are mapped to a different response than the target. A ubiquitous finding across a wide variety of distracter interference tasks (e.g., Stroop, Flanker, Simon) is that performance is slower and less accurate in incongruent than in congruent trials. This *congruency effect* indicates that selective attention does not completely filter irrelevant information.

It is interesting, however, that the size of the congruency effect varies systematically with the congruency of the previous trial, suggesting that the efficiency of selective attention varies from one trial to the next (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Gratton, Coles, & Donchin, 1992). Specifically, the congruency effect is smaller when the previous trial was incongruent than when it was congruent. As we discuss next, there is a heated debate regarding the psychological processes that trigger this *congruency sequence effect* (CSE) (Egner, 2007).

Cognitive Control Versus Learning and Memory Accounts

On one side of the debate, some researchers argue the CSE indexes trial-by-trial adjustments of cognitive control. One view in this domain is that participants expect the nature of irrelevant information in the current trial (i.e., congruent or incongruent) to repeat in the next trial and adjust attention accordingly (Gratton et al., 1992). For example, following an incongruent trial, participants expect to encounter an incongruent trial again and thus reduce attention to the distracter, thereby reducing the congruency effect. A second view is that the CSE is driven by heightened response conflict in incongruent trials (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Specifically, the detection of response conflict in one trial triggers control processes to allocate greater attention to the target in the next trial, which reduces the congruency effect. A third view is that the CSE is triggered by heightened negative affect in incongruent trials (Fritz & Dreisbach, 2013), which leads participants to increase effort toward identifying the target in the next trial and results in a smaller congruency effect. A fourth view is that the CSE is driven by top-down suppression of the response associated with the distracter in incongruent trials; this suppression persists to the next trial and thereby reduces the congruency effect (Ridderinkhof, 2002). Although each of these views posits that a unique process triggers the CSE, they share in

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common the assumption that the CSE indexes trial-by-trial top-down adjustments of cognitive control.

While the *cognitive control* view described above remains popular, an important challenge was put forward by Mayr, Awh, and Laurey (2003). These authors reported that the CSE in a typical two-choice flanker task (i.e., a task with two stimuli and two responses) vanished when trials with stimulus and response repetitions were (a) removed from the analysis "after the fact" or (b) prevented from occurring in the original trial sequence. To explain this result, they showed that exact stimulus and response repetitions, which speed performance, occur more frequently when congruency repeats across consecutive trials than when it does not. Thus, both congruent trials that are preceded by other congruent trials (cC trials) and incongruent trials that are preceded by other incongruent trials (iI trials) are performed relatively quickly. In contrast, congruent trials preceded by incongruent trials (iC trials) and incongruent trials preceded by congruent trials (cI) are performed relatively slowly. Since this pattern of performance yields a CSE, Mayr and colleagues argued the CSE could be explained by stimulus and response repetitions. Similarly, feature integration theory posits that the CSE occurs because the four possible congruency sequences (cC, cI, iC, iI) are associated with distinct types of feature (i.e., stimulus and/or response) repetitions, including, but not limited to, exact stimulus repetitions (Hommel, Proctor, & Vu, 2004). These considerations led to the *learning and memory* view of the CSE, which posits that the CSE indexes learning and memory processes that are confounded with congruency sequence in the vast majority of distracter interference tasks (Egner, 2007; Schmidt, 2013).

In response to Mayr et al.'s (2003) findings, proponents of the cognitive control view investigated whether a CSE could be observed independent of feature repetitions. The typical approach was to increase the size of the stimulus and response sets, thereby reducing the frequency of exact stimulus and response repetitions (Akçay & Hazeltine, 2007; Kerns et al., 2004; Ullsperger, Bylsma, & Botvinick, 2005). For instance, using a digit flanker task with nine possible stimuli and nine possible responses, in which feature repetitions were very infrequent, Ullsperger et al. (2005) reported a significant CSE. They therefore argued that there is more to the CSE than just stimulus and response repetitions. Based on similar results from the Stroop and Simon tasks, other researchers drew the same conclusion (for a review, see Egner, 2007).

Proponents of the learning and memory view of the CSE, however, recently noted that tasks like the one used by Ullsperger et al. (2005) introduce a new confound: contingency learning biases (Mordkoff, 2012; Schmidt & De Houwer, 2011). In any distracter interference task with more than two stimuli and two responses, there are fewer unique congruent stimuli than unique incongruent stimuli. For example, in a 3-choice flanker task involving the letters A, B, and C, there are three unique congruent stimuli (AAA, BBB, CCC) and six unique incongruent stimuli (BAB, CAC, ABA, CBC, ACA, BCB). For this reason, to equate the number of congruent and incongruent trials in *n*-alternative forced choice (AFC) distracter interference tasks with more than two possible stimuli and responses, thereby maximizing the number of trials in each of the four congruency sequences, researchers often present each unique congruent stimulus far more often than they present each incongruent stimulus (Hazeltine, Lightman, Schwarb, & Schumacher, 2011; Ullsberger et al., 2005). This procedure leads each distracter to become more strongly associated with the congruent response than with any of the possible incongruent responses. In other words, it introduces a contingency wherein participants can learn to predict that each distracter is more strongly associated with the high-probability (i.e., high-contingency) congruent response than with each low-probability (i.e., low-contingency) incongruent response. This *contingency effect* speeds response times in high-contingency congruent trials, relative to low-contingency incongruent trials (Schmidt & De Houwer, 2011). Moreover, it is larger after a high-contingency congruent trial than after a low-contingency incongruent trial, a modulation that has been dubbed a *sequential contingency effect* and which produces a pattern of behavioral performance that mimics the CSE (Schmidt, 2013; Schmidt & De Houwer, 2011). Thus, although not due to feature repetitions, the CSE in many studies involving more than two stimuli and responses may have been driven by a sequential contingency effect.

Controlling for Feature Integration and Contingency Learning Confounds

Two main approaches have been employed to investigate whether a CSE can be observed independent of both feature integration and contingency learning confounds. Both make use of distracter interference tasks with at least four possible stimuli and responses, which is necessary for ensuring that there are some trials in which no features from the previous trial are repeated. Further, both associate each distracter with the congruent response as often as it is associated with an incongruent response, thereby eliminating contingency learning confounds. The two approaches differ, however, with regard to whether feature repetitions are allowed to occur in the original trial sequence. The first approach allows trials with feature repetitions to occur but discards them in subsequent analyses of the CSE, potentially resulting in a loss of statistical power (Mayr et al., 2003; Mordkoff, 2012). The second approach prevents trials with feature repetitions from occurring by dividing the stimulus-response (S-R) mapping for an *n*-AFC task into a pair of *n*/2 S-R mappings and alternating across trials between stimuli associated with these two mappings (Jiménez & Méndez, 2013; Mayr et al., 2003). For example, Mayr et al. (2003) divided a 4-AFC Flanker task involving leftward, rightward, upward, and downward pointing arrow stimuli into a pair of 2-AFC Flanker tasks involving (a) leftward and rightward pointing arrows and (b) upward and downward pointing arrows. They then alternated across trials between stimuli composed of leftward and/or rightward pointing arrows and stimuli composed of upward and/or downward pointing arrows. Critically, the CSE in the three most popular distracter interference tasks—Stroop, Flanker, and Simon—vanishes when employing the first approach (Mordkoff, 2012; Schmidt & De Houwer, 2011). The CSE also vanishes in the Stroop and Flanker tasks when employing the second approach (to our knowledge, this approach has not yet been applied to the Simon task) (Jiménez & Méndez, 2013; Mayr et al., 2003). Given such findings, several researchers have questioned whether a CSE can be observed independent of feature integration and contingency learning confounds (Mayr et al., 2003; Mordkoff, 2012; Nieuwenhuis et al., 2006; Schmidt & De Houwer, 2011).

Using the first approach above, however, Kunde and Wuhr (2006) reached a different conclusion based on data from a 4-AFC prime-probe task. In prime-probe tasks, the prime, or distracter, appears prior to the probe, or target. In each trial of Kunde and Wuhr's task, participants indicated the direction in which a target arrow pointed (left, right, up, or down) just after observing a distracter arrow that pointed in the same or in a different direction (left, right, up, or down). The authors observed a significant CSE. As the authors noted, however, a limitation of their study was that, even in trials with no exact feature repetitions, the arrows in each trial were rotated versions of the arrows in the previous trial. This left open the possibility that the CSE indexed feature integration processes coupled with a mental rotation strategy.

Given the theoretical importance of determining whether a CSE can be observed independent of the typical learning and memory confounds for understanding the psychological processes that minimize distraction, we recently attempted to replicate Kunde and Wuhr's (2006) findings using a prime-probe task that better controls for feature integration confounds (Schmidt & Weissman, 2014). In each trial of our task, participants discriminated the direction indicated by a target word (*Left*, *Right*, *Up*, or *Down*) that was preceded by a distracter array consisting of three identical distracter words (*Left*, *Right*, *Up*, or *Down*). Of importance, unlike in the arrow version of the prime-probe task, none of the four direction words could be rotated to match a different direction word (e.g., *Left* could not be rotated to match *Right*). To maximize statistical power, we employed the second approach for eliminating feature integration and contingency learning confounds, which involves preventing feature repetitions from occurring in the trial sequence. Specifically, analogous to Mayr et al. (2003), we divided the S-R mapping for our 4-AFC task into a pair of 2-AFC S-R mappings, one involving the words *Left* and *Right* and the other involving the words *Up* and *Down*. We then alternated across trials between stimuli composed of the words *Left* and/or *Right* and stimuli composed of the words *Up* and/or *Down*. Critically, we observed a robust CSE in this task. We therefore concluded that a CSE can be observed independent of feature integration and contingency learning confounds. In the present study, we aimed to extend these findings by determining the critical task parameters that are necessary for observing CSEs in the absence of such confounds.

The Present Study

The goal of the present study was to investigate why a CSE can be observed independent of the typical learning and memory confounds more easily in the prime-probe task than in the classic Stroop, Flanker, or Simon tasks. As described next, multiple differences between the prime-probe task and the other three tasks led us to consider three main hypotheses.

The *perceptual modulation* hypothesis posits that presenting the distracter before the target allows selective attention to better modulate the perceptual processing of the target and/or the distracter. Multiple cognitive control accounts posit that the CSE indexes modulations of perceptual attention (Botvinick et al., 2001; Gratton et al., 1992). Moreover, numerous findings from the cognitive neuroscience literature suggest that response conflict in incongruent trials is resolved by increasing perceptual attention to the target (Egner & Hirsch, 2005; Polk, Drake, Jonides, Smith, & Smith, 2008; Weissman, Warner, & Woldorff, 2004) and/or by decreasing perceptual attention to the distracter (Polk et al., 2008). Of importance, it is well-established that humans can orient attention to particular points in time (Nobre, Correa, & Coull, 2007). Further, it has been suggested that deploying perceptual attention at different times after incongruent and congruent trials may contribute to the CSE in prime-probe tasks (Hazeltine et al., 2011). Thus, presenting the distracter before the target, rather than simultaneously with it, may yield a CSE because it allows attention to better modulate the perceptual processing of the target and/or the distracter.

The *response modulation* hypothesis posits that presenting the distracter before the target allows attention to better modulate response-related aspects of target or distracter processing. As an example of the former, the temporal learning hypothesis posits that participants temporarily lower their threshold for responding at around the time they responded in the previous trial, based on an expectation that a decision will be reached by that time (Schmidt, 2013). Since mean response time differs systematically between congruent and incongruent trials, this strategy facilitates response times when congruency repeats across consecutive trials (i.e., cC and iI trials), relative to when it does not, thereby producing a CSE (Schmidt, 2013). This view has difficulty explaining why the CSE is absent in the classic Stroop, Flanker, and Simon tasks when controlling for feature integration and contingency learning confounds (Mordkoff, 2012; Schmidt, 2013). However, the CSE may be larger in the prime-probe task than in the other tasks because the distracter serves as a "warning cue" that the target will appear, thereby increasing the probability that the response threshold will be lowered at the time of the expected response.

Another instance of a response modulation hypothesis is the *activation-suppression* hypothesis, which posits that presenting a distracter before (relative to with) a target increases the time available for control processes to suppress the response engendered by the distracter before the target response comes online. An extension of dual-route models of distracter interference tasks (Kornblum, Hasbroucq, & Osman, 1990), in which distinct pathways activate responses associated with distracter and target stimuli, this hypothesis posits that the response associated with the distracter is gradually suppressed over the course of each trial. Further, such suppression is posited to be more effective (a) when the distracter response is activated before the target response, as in the Simon and prime-probe tasks (Burle, van den Wildenberg, & Ridderinkhof, 2005; Ridderinkhof, 2002), and (b) after incongruent versus congruent trials due to enhanced inhibition of the pathway through which all distracter responses become active (Burle et al., 2005; Ridderinkhof, 2002). Thus, the CSE in the Simon and prime-probe tasks may occur because the distracter response is activated before the target response and can therefore be more effectively suppressed after incongruent trials (van Campen, Keuken, van den Wildenberg, & Ridderinkhof, 2014).

One might wonder whether the degree to which the distracter response becomes activated earlier than the target response is greater in the Simon task than in the Stroop and Flanker tasks. Consistent with this view, recent findings from event-related potentials (ERPs) indicate the distracter response becomes activated about 100 ms earlier in the Simon task than in the Flanker task (Mansfield, van der Molen, Falkenstein, & van Boxtel, 2013). The authors of this prior study concluded that lateralized distracters in the Simon task engender irrelevant response activation much more quickly than symbolic arrow distracters in the Flanker task. Since the Stroop task also employs symbolic distracters (i.e., words), the distracter response would likely also become activated much earlier in the Simon task than in the Stroop task. Such considerations suggest that the distracter response becomes activated earlier than the target response to a greater degree in the Simon task than in the Stroop and Flanker tasks. Thus, any contribution of response suppression to the CSE should be more visible in the Simon task than in Stroop and Flanker tasks (for converging evidence, see Burle, Spieser, Servant, & Hasbroucq, 2013). This view may appear to contradict a recent finding indicating that the CSE is absent in the Simon task when controlling for the typical confounds (Mordkoff, 2012). However, this finding was observed after removing feature repetitions by discarding large numbers of trials. A lack of statistical power might therefore have prevented the CSE from being observed.

Our third hypothesis was motivated by other differences between the prime-probe task and the Stroop, Simon, and/or Flanker tasks. In particular, the *spatial overlap* hypothesis was motivated by the fact that, unlike in the classic Flanker task, in the prime-probe task the distracter and the target appear at the same location. Such spatial overlap makes it more difficult to filter a distracter (Eriksen & Eriksen, 1974), which could increase the degree to which distracter processing engenders a CSE.

In sum, we predicted that several factors, either alone or in combination, might explain why the CSE can be observed more easily in the prime-probe task than in the Stroop, Flanker, and Simon tasks independent of the typical learning and memory confounds. We therefore anticipated that identifying these factors could require numerous experiments involving a large number of participants. For this reason, we conducted our studies on Amazon's Mechanical Turk (AMT), an online crowdsourcing system. Prior studies on AMT have qualitatively replicated the results of laboratory distracter interference tasks, such as the Stroop and Flanker tasks (Crump, McDonnell, & Gureckis, 2013; Simcox & Fiez, 2014). Thus, we expected that AMT would allow for an efficient and accurate investigation of our hypotheses.

We also expected that conducting our experiments on AMT would confer some additional advantages (Crump et al., 2013). First, workers on AMT are usually more diverse (in terms of age, socioeconomic status, etc.) than typical study samples (consisting largely of college undergraduates), which suggests that data obtained on AMT might better generalize to the population at large. Second, although certain aspects of the experiment cannot be controlled on AMT (e.g., the stimulus size in degrees of visual angle), significant results may indicate effects that are robust to variability in theoretically uninteresting task parameters. Third, online experiments are often more transparent to researchers than their laboratory counterparts, because the trial sequences and underlying computer code can be viewed from anywhere on the Internet. Such experiments might therefore be easier to replicate precisely than corresponding laboratory studies. For these reasons, we anticipated that conducting our experiments on AMT would prove to be an effective method for investigating our hypotheses.

Experiment 1

In Experiment 1, we sought to replicate our recent finding of a CSE without feature integration or contingency learning confounds in the prime-probe task (Schmidt & Weissman, 2014). We reasoned that replicating this finding on AMT would provide converging evidence for the view that there is more to the CSE than feature integration and contingency learning confounds. It would also validate the use of Internet-based data collection in subsequent experiments involving similar tasks. Table 1 lists the predictions made by each hypothesis in Experiments 1–3 about when a CSE will be observed.

Method

Participants. In each experiment, we sought to recruit 50 adults in each task or critical task condition to ensure adequate power for subsequent statistical analyses. This was most important in Experiment 3, which involved between-participants statistical comparisons. In practice, however, there were usually a few individuals who completed the task but did not submit their data properly on AMT. Thus, we typically wound up with slightly fewer than 50 participants in each task or critical task condition. Further reducing our sample size by a small amount, in each experiment we excluded all participants whose mean overall accuracy was less than 70% and all participants whose mean overall RT was greater or less than 2.5 standard deviations from the group's overall mean RT.

Table 1
Predictions of the Hypotheses Tested in Experiments 1–3

	Condition(s) showing a CSE
Experiment 1	
Perceptual modulation	Prime-probe task
Response modulation	Prime-probe task
Spatial overlap	Prime-probe task
Learning and memory	None
Experiment 2	
Perceptual modulation	None
Response modulation (temporal learning)	None
Response modulation (activation-suppression)	Simon
Spatial overlap	Stroop and Simon
Experiment 3	
Activation-suppression AND spatial overlap	Central distracter present
Activation-suppression only	Central distracter present and absent

Note. CSE = congruency sequence effect.

We tried to ensure that the data for each experiment and experimental condition came from different AMT workers by capitalizing on the fact that such workers are identified through unique identification numbers. This allowed us to identify, post hoc, any workers who participated in multiple experiments and/or experimental conditions. We observed only one such case and excluded the data from the second experiment in which this worker participated.

Forty-five adults participated in Experiment 1. Two participants were excluded because their mean RT across all conditions was greater than 2.5 standard deviations from the group mean RT. Data from the remaining 43 individuals were employed in subsequent analyses. All of these individuals self-reported their sex and age online (14 female, 29 male; mean age, 30.8 years, age range, 19–66 years).

Stimuli. Each distracter consisted of three, perceptually identical words (color, white; font size, 48 points) stacked vertically at the center of the screen. The four possible words were *Up*, *Down*, *Left*, and *Right*. Each target consisted of a single word—*Left*, *Right*, *Up*, or *Down*—at the center of the screen (color, white; font size, 77 points). These stimuli were always presented on a gray background.

In all of our online experiments, stimulus delivery and response collection were enabled by Javascript. This required participants to download the task to their web browsers first and then run the task locally. Thus, there were no timing issues related to the speed of the Internet connection. Moreover, since modern computer monitors usually have refresh rates of 60Hz (16.67 ms per frame), the stimulus durations we employed (133 ms and 33 ms) corresponded, respectively, to two and eight refreshes, which can be directly implemented through Javascript programming.

Task and design. Three stimuli were presented sequentially in each 2-s trial (Figure 1a): the distracter (duration, 133 ms), a blank screen (duration, 33 ms), and the target (duration, 133 ms). Participants were instructed to identify the target word as quickly as possible without making mistakes by pressing one of four keys on their computer keyboard. Specifically, participants were instructed to press the *F* (left middle finger), *G* (left index finger), *J* (right index finger), or *N* (right middle finger) key of their computer keyboard, respectively, to indicate that the target word was *Left*, *Right*, *Up*, or *Down*.

As in certain prior studies of the CSE (Jiménez & Méndez, 2013; Mayr et al., 2003), we prevented feature repetitions across trials by dividing the 4-AFC S-R mapping for our task into a pair of 2-AFC S-R mappings and alternating between these mappings across trials. Specifically, we alternated across trials between stimuli composed of the words *Left* and/or *Right* and stimuli composed of the words *Up* and/or *Down*. Congruent and incongruent trials were presented equally often within each of these distinct 2-AFC S-R mappings (i.e., 50% of the trials were congruent and 50% were incongruent), thereby preventing contingency learning biases (Mordkoff, 2012; Schmidt & De Houwer, 2011). Finally, trial congruency varied independently of which S-R mapping was relevant in the previous and current trial. Every participant completed four 97-trial blocks of the task, each of which provided a maximum of 96 trials for data analysis (since the first trial of each block was always excluded from the analyses). The task instructions and practice trials can be viewed at: https://dl.dropboxusercontent.com/u/163901707/AMT/DW_v1/FlankerMain.html

Procedure. Online participants were directed to the task via AMT. Each participant read the online instructions before completing a brief practice session consisting of 24 trials. During the practice session only, the S-R mapping was presented (duration, 1,500 ms) prior to each trial. After the practice session, the participant gave informed consent and voluntarily completed a demographic survey that requested gender and age information. Finally, the participant performed the task, submitted his or her responses to AMT, and was compensated via AMT (approximately $3 per hour in all experiments, because we always rounded the payment up to the nearest 5-cent increment).

Data analysis. Practice trials and the first trial of each run were not analyzed. Prior to analyzing each participant's response time (RT) data, errors, trials immediately following errors, outliers (i.e., trials with RTs greater than 2.5 standard deviations from the conditional mean), and trials immediately following outliers were discarded. In total, 3.45% of the trials were errors and 2.11% were outliers. The same trials were discarded prior to analyzing each

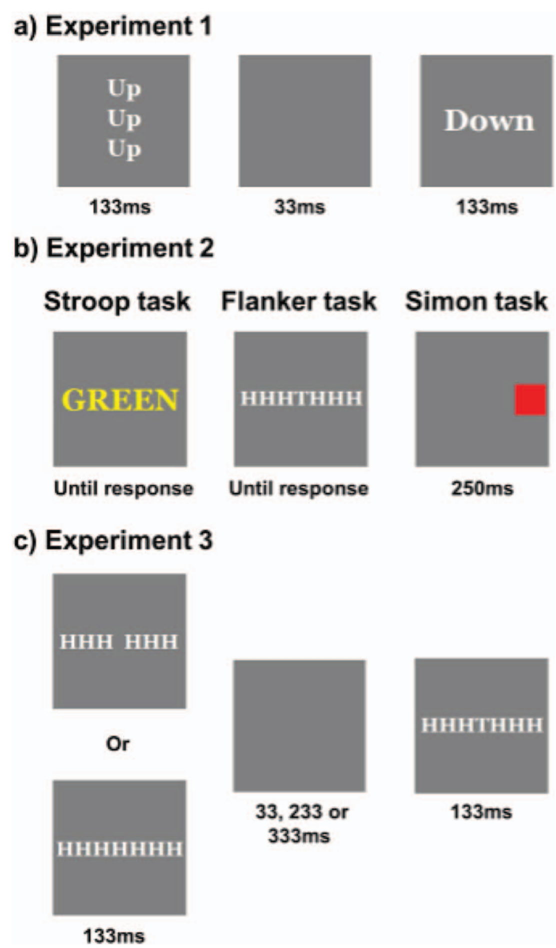

Figure 1. The tasks we employed in the present study. (a) In Experiment 1, participants performed the prime-probe task. (b) In Experiment 2, participants performed the Stroop task (left), Flanker task (middle), or Simon task (right). (c) In Experiment 3, participants performed the temporal letter flanker task. The color version of this figure appears in the online article only.

participant's error rate data, with the exception of errors (since errors were the dependent measure in this analysis).

After excluding these trials, mean correct RT and mean percentage error were calculated in each participant for the four congruency trial sequences in the experiment: cC, cI, iC, and iI. Separate repeated-measures analyses of variance (ANOVAs) with two factors— current congruency (congruent, incongruent) and previous congruency (congruent, incongruent) —were employed to analyze mean RT and mean error rate. Table 2 indicates the overall mean RT, congruency effect, and congruency sequence effect (in ms) for the main conditions of Experiments 1–3.

Results

Mean RT. First, as expected, there was a main effect of current congruency, $F(1, 42) = 311.383$, $p < .001$, $\varsigma_p^2 = .881$, indicating slower RTs in incongruent trials (828 ms) than in congruent trials (755 ms). Second, replicating prior findings in the prime-probe task (Kunde & Wuhr, 2006; Schmidt & Weissman, 2014), there was an interaction between previous congruency and current congruency (i.e., a CSE), $F(1, 42) = 75.309$, $p < .001$, $\varsigma_p^2 = .642$, indicating less interference after incongruent trials (64 ms) than after congruent trials (84 ms) (see Figure 2). Tests of simple effects revealed that mean RT was longer in cI trials (833 ms) than in iI trials (822 ms), $F(1, 42) = 20.327$, $p < .0001$, $\varsigma_p^2 = .326$, and longer in iC trials (762 ms) than in cC (747 ms) trials, $F(1, 42) = 67.203$, $p < .001$, $\varsigma_p^2 = .615$. No other effects were significant.

Mean error rate. An analogous ANOVA on mean error rate revealed a main effect of current congruency, $F(1, 42) = 11.972$, $p = .001$, $\varsigma_p^2 = .22$. As expected, mean error rate was higher in incongruent trials (3.8%) than in congruent trials (1.8%). There was also a main effect of previous congruency, $F(1, 42) = 4.653$, $p < .05$, $\varsigma_p^2 = .10$, because mean error rate was lower when the previous trial was incongruent (2.4%) as compared to congruent (3.2%), $F(1, 15) = 11.608$, $p < .005$, $\varsigma_p^2 = .90$. No other effects were significant.

Discussion

In Experiment 1, we replicated our previous laboratory findings indicating a CSE in the prime-probe task independent of feature integration and contingency learning confounds (Schmidt & Weissman, 2014). This result provides converging support for the view that a CSE can be observed independent of the typical confounds. It also validates the use of AMT for online data collection in subsequent experiments involving similar tasks.

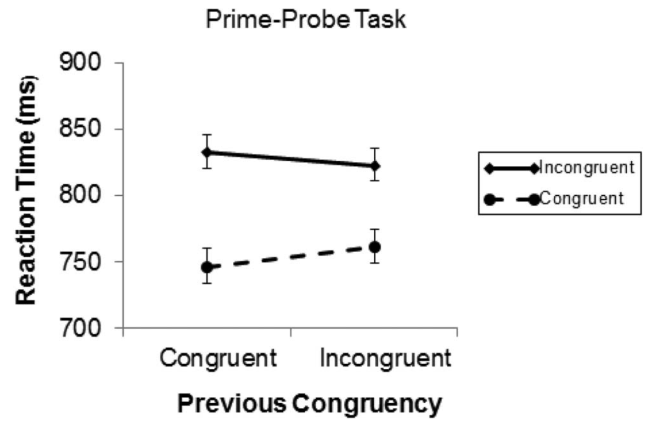

Figure 2. The congruency sequence effect in the prime-probe task of Experiment 1. We found that cC trials were performed more quickly than iC trials and that iI trials were performed more quickly than cI trials.

Table 2
Descriptive Statistics (in Ms) From Experiments 1–3

	Mean RT	I-C	CSE
Experiment 1			
Prime-probe task	792	73	20
Experiment 2			
Stroop task	861	92	−7
Flanker task	864	53	8
Simon task	823	45	21
Experiment 3			
Temporal flanker task			
Central distracter present	1,257	97	34
Central distracter absent	1,177	48	3

Note. I-C = incongruent-congruent; CSE = congruency sequence effect, which is calculated as: (cI − cC) − (iI − iC).

Experiment 2

In Experiment 2, we began to investigate our hypotheses concerning why a CSE is more easily observed in the prime-probe task than in the Stroop, Flanker, or Simon tasks. As described in the Introduction, we considered the perceptual modulation hypothesis, the response modulation hypothesis, and the spatial overlap hypothesis.

To begin distinguishing among these hypotheses, we asked participants to perform 4-AFC versions of the classic Stroop, Flanker, and Simon tasks, which did not engender feature integration or contingency learning confounds. The perceptual modulation hypothesis does not predict a CSE in any of these tasks, because the target and distracter always appear at the same time. In contrast, the spatial overlap hypothesis predicts a CSE in the Simon and Stroop tasks, but not in the Flanker task, because in the former tasks the distracter and the target appear at the same location.

The predictions of the response modulation hypothesis depend on how presenting the distracter before the target in the prime-probe task influences response-related processing. If it serves as a warning signal that the target is about to appear, which promotes a temporary reduction of the response threshold at the time of the expected response (Schmidt, 2013), then a CSE should be absent in the Stroop, Flanker, and Simon tasks. Indeed, in these tasks, there is no warning signal because the distracter always appears simultaneously with the target. On the other hand, if presenting the distracter before the target allows the distracter response to become activated before the target response, which ultimately leads to more effective suppression of the distracter response, then a CSE should be absent in the Stroop and Flanker tasks but present in the Simon task. Indeed, only in the Simon task is the distracter (spatial location: left, right, up, or down) more automatically mapped to a response (left, right, up, or down key press) than the target (color: red, blue, green, or yellow). For this reason, the distracter in the Simon task is likely to be translated into a response much more quickly than the target in the Simon task (Ridderinkhof, 2002; Wylie, Ridderinkhof, Bashore, & van den Wildenberg, 2010), relative to the Stroop and Flanker tasks.

Method

Stroop task.

Participants. Forty-seven individuals participated in the study. Prior to analyzing the test trials, three participants were excluded because they failed to perform correctly on at least 70% of the trials. An additional participant was excluded because his mean RT across all conditions was greater than 2.5 standard deviations from the group mean RT. Data from the remaining 43 individuals were employed in subsequent analyses. All of these individuals self-reported their sex and age online (27 female, 16 male; mean age, 32.2 years, age range, 19–72 years).

Stimuli. The stimuli consisted of four words (RED, BLUE, GREEN, or YELLOW; font size, 72 points) presented in one of four colors (red, blue, green, or yellow). However, each word was presented in only two of the possible four colors (see below).

Task and design. In each trial, a Stroop stimulus appeared at the center of the computer screen until the participant responded (Figure 1b, left). Participants were instructed to identify the color in which the word appeared as quickly as possible without making mistakes by pressing one of four keys on the computer keyboard. To do so, they used their left middle finger (*z*), left index finger (*x*), right index finger (*n*), or right middle finger (*m*). The color-to-response mapping was randomized across participants. Trials were separated by a 1-s intertrial interval (ITI).

Analogous to Experiment 1, the experimental design involved dividing the 4-AFC S-R mapping into a pair of 2-AFC S-R mappings, each of which consisted of two words and two colors. Colors and words were randomly assigned to each of the two S-R mappings across participants. For example, a given participant might have been assigned one mapping involving red and blue colors and words and a second mapping involving green and yellow colors and words. Within each mapping, each word was presented equally often in the congruent and incongruent color. As in Experiment 1, participants alternated between the stimuli associated with these mappings across trials. In total, there were four 80-trial task blocks. All other aspects of the design were identical to the design of Experiment 1. The task instructions and practice trials can be viewed at: https://dl.dropboxusercontent.com/u/163901707/AMT/wStroop_1/wStroopMain.html

Procedure. The procedure was identical to that in Experiment 1.

Data analysis. The data analysis was identical to that in Experiment 1. In total, 4.32% of the trials were errors and 2.55% were outliers.

Flanker task.

Participants. Forty-eight individuals participated in the study. Prior to analyzing the test trials, six participants were excluded because they failed to perform correctly on at least 70% of the trials. One additional participant was excluded because her mean RT across all conditions was greater than 2.5 standard deviations from the group mean RT. Data from the remaining 41 individuals were employed in subsequent analyses. All of these individuals self-reported their sex online (22 female, 19 male). However, only 40 self-reported their age (mean age, 35.0 years, age range, 20–64 years).

Stimuli. The stimuli consisted of four letters (M, T, H or S; size, 60 points). In each trial, one of the letters, the target, appeared at the center of the computer screen. Six additional letters, or flankers, appeared immediately to the left (three letters) and immediately to the right (three letters) of the target. The six flankers were identical copies of a single letter. Each target was paired with just two of the four possible flanker letters (see below).

Task and design. In each trial, the target and flankers were presented simultaneously at the center of the computer screen (duration, 250 ms; Figure 1b, center). Participants were instructed to indicate the identity of the target letter by pressing *Z* (left middle finger), *X* (left index finger), *N* (right index finger), or *M* (right middle finger) as quickly as possible without making mistakes (the target-response mapping was randomized across participants). After the stimulus was erased, a fixation cross was presented until the participant responded. Trials were separated by a 1-s ITI.

Analogous to Experiment 1, the experimental design involved dividing the 4-AFC S-R mapping into a pair of 2-AFC S-R mappings, each of which consisted of two letters and two possible responses. The four letters were randomly assigned to the two S-R mappings in each participant. For example, a given participant might have been assigned one mapping involving the letters M and T and a second mapping involving the letters H and S. Within each mapping, each target letter was presented equally often with the congruent and incongruent flanker letters. As in Experiment 1, participants alternated between the stimuli associated with these mappings across trials. In total, there were four 80-trial task blocks. All other aspects of the design were identical to the design of Experiment 1. The task instructions and practice trials can be viewed at: https://dl.dropboxusercontent.com/u/163901707/AMT/lFlanker_1/FlankerMain.html

Procedure. The procedure was identical to that in Experiment 1.

Data analysis. The data analysis was identical to that in Experiment 1. In total, 4.73% of the trials were errors and 2.01% were outliers.

Simon task.

Participants. Fifty individuals participated in the study. Prior to analyzing the test trials, three participants were excluded because they failed to perform correctly on at least 70% of the trials. Further, one was excluded because her mean RT across all conditions was greater than 2.5 standard deviations from the group mean RT. Data from the remaining 46 individuals were employed in subsequent analyses. Of these individuals, 41 self-reported their sex online (22 female, 19 male) and 45 self-reported their age (mean age, 33.0 years, age range, 20–72 years).

Stimuli. The stimuli consisted of colored squares (red, blue, green or yellow; size, 100 × 100 pixels) presented above, below, to the left, and to the right of the center of the computer screen. The relevant target was the square's color; the irrelevant distracter was the square's location. Each color was paired with just two of the four possible spatial locations (see below).

Task and design. In each trial, a colored square appeared for 250 ms (Figure 1b, right). Participants were instructed to indicate the identity of the square's color as quickly as possible without making mistakes by pressing the left arrow key (left middle finger), the right arrow key (left index finger), the up arrow key (right middle finger), or the down arrow key (right index finger) on the computer keyboard (the color-response mapping was randomized across participants). After the stimulus was erased, a fixation cross appeared at the center of the computer screen until the participant responded. Trials were separated by a 1-s ITI.

Analogous to Experiment 1, the experimental design involved dividing the 4-AFC S-R mapping into a pair of 2-AFC S-R mappings, each of which consisted of two colors and two spatial locations. The four colored squares were randomly assigned to the two S-R mappings in each participant. For example, a given participant might have been assigned one mapping involving red and blue squares appearing to the left and right of the screen center and a second mapping involving green and yellow squares appearing above and below the screen center. Within each mapping, the response associated with each target color was congruent (50% of trials) or incongruent (50% of trials) with the spatial location at which the colored square appeared. As in Experiment 1, participants alternated between the stimuli associated with these mappings across trials. In total, there were four 80-trial task blocks. All other aspects of the design were identical to the design of Experiment 1. The task instructions and practice trials can be viewed at: https://dl.dropboxusercontent.com/u/163901707/AMT/Simon_1/wSimonMain.html

Procedure. The procedure was identical to that in Experiment 1.

Data analysis. The data analysis was identical to that in Experiment 1. In total, 4.98% of the trials were errors and 2.13% were outliers.

Results

Stroop task.

Mean RT. There was a main effect of current congruency, $F(1, 42) = 115.349$, $p < .001$, $\varsigma_p^2 = .733$, because mean RT was slower in incongruent trials (907 ms) than in congruent trials (815 ms). No other effects were significant including the interaction between previous congruency and current congruency (see Figure 3a).

Mean error rate. There were no significant effects. However, although the interaction between previous congruency and current congruency failed to achieve conventional levels of significance, $F(1, 42) = 3.797$, $p = .058$, $\varsigma_p^2 = .08$, there was numerically greater interference after congruent trials (1.6%) than after incongruent trials (0.2%).

Flanker task.

Mean RT. There was a main effect of current congruency, $F(1, 40) = 41.507$, $p < .001$, $\varsigma_p^2 = .509$, because mean RT was slower in incongruent trials (890 ms) than in congruent trials (837 ms). No other effects were significant including the interaction between previous congruency and current congruency (see Figure 3b).

Mean error rate. There was a main effect of current congruency, $F(1, 40) = 4.591$, $p < .05$, $\varsigma_p^2 = .103$, because mean error rate was higher in incongruent trials (4.2%) than in congruent trials (3.2%). No other effects were significant.

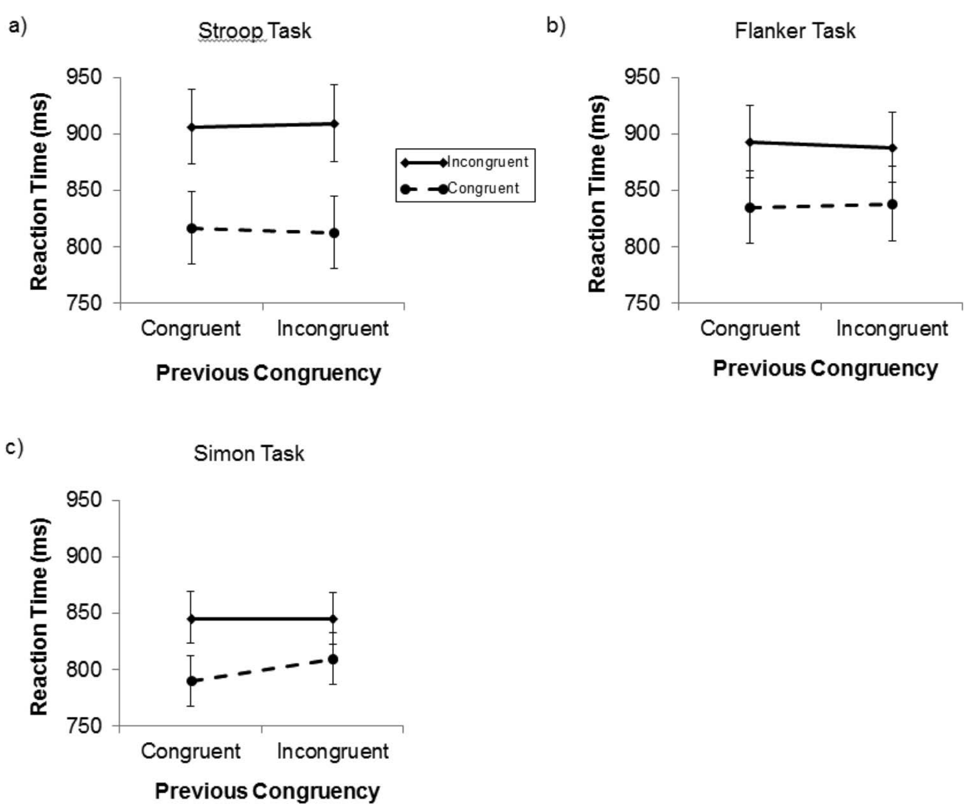

Figure 3. The congruency sequence effect in the Stroop, Flanker, and Simon tasks of Experiment 2. We did not observe a significant congruency sequence effect in either the (a) Stroop task or (b) Flanker task. In contrast, there was a significant congruency sequence effect in the Simon task (c). In the Simon task, cC trials were performed significantly faster than iC trials, but iI trials were not performed significantly faster than cI trials.

Simon task.

Mean RT. There were three significant effects. First, there was a main effect of current congruency, $F(1, 45) = 70.891$, $p < .001$, $\varsigma_p^2 = .612$, indicating that mean RT was slower in incongruent trials (845 ms) than in congruent trials (800 ms). Second, there was a main effect of previous congruency, $F(1, 45) = 5.876$, $p < .02$, $\varsigma_p^2 = .115$, because mean RT was slower when the previous trial was incongruent (827 ms) as compared to congruent (818 ms), consistent with previous findings indicating "postconflict" slowing (Ullsberger et al., 2005; Verguts, Notebaert, Kunde, & Wuhr, 2011). Third, as shown in Figure 3c, there was an interaction between previous congruency and current congruency, $F(1, 45) = 9.850$, $p < .005$, $\varsigma_p^2 = .180$, because the congruency effect was smaller after incongruent trials (35 ms) than after congruent trials (56 ms). Tests of simple effects revealed that mean RT was faster in cC trials (790 ms) than in iC trials (810 ms), $F(1, 45) = 12.257$, $p = .001$, $\varsigma_p^2 = .214$, but did not differ between iI trials (845 ms) and cI trials (846 ms), $F(1, 45) < 1$. No other effects were significant.

Mean error rate. There was a main effect of current congruency, $F(1, 45) = 15.998$, $p < .001$, $\varsigma_p^2 = .262$, because mean error rate was higher in incongruent trials (5.1%) than in congruent trials (2.4%). No other effects were significant.

Across-Task Analyses

As predicted by a variant of the response modulation hypothesis, the CSE in the mean RT data was significant in the Simon task but not in the Stroop and Flanker tasks. However, it remains unclear whether the CSE was significantly greater in the Simon task than in the other two tasks. We employed one-tailed Mann–Whitney *t* tests to investigate this hypothesis, because a Levene test indicated that across-participant variance in the CSE differed among the Simon, Stroop, and Flanker tasks, $F(2, 127) = 3.17$, $p = .0453$, which violates the assumption of equal variances made by ANOVA. These *t* tests revealed that the CSE in the mean RT data was indeed greater in the Simon task than in (a) the Stroop task ($U = 780$, $z = 1.72$, $p = .044$) and (b) the Flanker task ($U = 732$, $z = 1.79$, $p = .037$). For completeness, we also tested whether the CSE differed in the Stroop and Flanker tasks and found no significant difference ($U = 903$, $z = 0.19$, $p = .423$).

At least one cognitive control account—the conflict monitoring model—appears to posit that the size of the CSE should vary positively with the size of the congruency effect (Botvinick et al., 2001; Wendt, Kiesel, Geringswald, Purmann, & Fischer, 2014; Yeung, Cohen, & Botvinick, 2011). To investigate this possibility, we determined whether the congruency effect in the mean RT data was larger in the Simon task, which exhibited a relatively large CSE, than in the Stroop and Flanker tasks, which exhibited relatively small CSEs. Unlike for the across-experiment comparisons of the CSE above, the assumption of equal variances was not violated, $F(2, 127) = 1.48$, $p > .231$. Therefore, to test our hypothesis, we conducted a one-way ANOVA on the congruency effect in the mean RT data with Task (Stroop, Simon, Flanker) as a between-participants factor.

The ANOVA revealed a significant main effect of Task, $F(2, 127) = 11.47$, $p < .001$. Post hoc *t* tests (two-tailed) revealed that the congruency effect was significantly larger in the Stroop task (93 ms) than in both (a) the Flanker task (53 ms, $t(82) = 3.42$, $p = .002$) and (b) the Simon task (45 ms, $t(87) = 4.72$, $p < .001$; the congruency effect did not differ between the Flanker and the Simon tasks, $t(85) = 0.86$). Thus, the CSE was larger in the Simon task than in the Stroop task, even though the congruency effect was larger in the Stroop task than in the Simon task.[1] We acknowledge that the degree to which the conflict monitoring model predicts a positive relationship between the size of the congruency effect and the size of the CSE may be reduced when across-task comparisons are made, because control adjustments in the model are scaled by a learning parameter that may differ across tasks (Botvinick et al., 2001). Still, the present findings do not appear to provide clear support for this account of the CSE.

Discussion

Our findings in Experiment 2 fit with a variant of the response modulation hypothesis in which the CSE emerges when S-R translation is completed more quickly for a distracter than for a target. Specifically, we observed a CSE in the Simon task, wherein the irrelevant distracter is likely translated into a response much more quickly than the target (Ridderinkhof, 2002; Wylie et al., 2010). In contrast, we did not observe a CSE in the Stroop or Flanker tasks, wherein the arbitrary S-R mappings likely result in S-R translation for the distracter and the target finishing at more similar times, relative to the Simon task. Finally, the CSE was significantly larger in the Simon task than in the Stroop and Flanker tasks, even though the congruency effect was significantly smaller in the Simon task than in the Stroop task. These findings provide initial support for a variant of the response modulation hypothesis, which suggests that whether S-R translation is more rapid for a distracter than for a target influences whether a CSE is observed.

Our finding of a CSE in the Simon task may appear atypical given recent data indicating the CSE is absent in the Simon task after eliminating feature integration and contingency bias confounds (Mordkoff, 2012). As we noted earlier, however, feature repetitions in this prior study were allowed to occur in the trial sequence and were eliminated by excluding large numbers of trials from the data analyses. Thus, the discrepancy between our findings and these prior results may reflect differences in statistical power between the two studies. Consistent with this view, our study also employed many more trials and participants than did this prior study.

Finally, although our findings support a variant of the response modulation hypothesis, they do not exclude the possibility that other factors help to produce a CSE. For example, observing a CSE may require not only that the distracter response becomes active before the target response but also that the distracter appears in the same location as the target, as posited by the spatial overlap hypothesis. Since the Stroop task in Experiment 2 did not produce a CSE, one might conclude that whether the target and distracter appear in the same location plays no role in producing a CSE. However, it is possible that spatial overlap helps to produce a CSE only when the degree to which the distracter response becomes

[1] An independent samples *t* test (two-tailed, not assuming equal variances) confirmed that the congruency effect was significantly smaller in the Simon task than in the Stroop task even when it was calculated as a percentage of mean RT for each participant, $t(87) = 5.798$, $p < .001$.

active earlier than the target response is relatively high. We investigated this possibility in Experiment 3.

Experiment 3

In Experiment 3, we further investigated the hypothesis that a CSE emerges when a distracter can be translated into a response more quickly than a target. We reasoned that if this hypothesis is correct, then it might be possible to induce a CSE in, for example, the letter flanker task by presenting the distracters before the target. Since the time at which a CSE might appear was unknown, we included a between-participants manipulation of the interstimulus-interval (ISI), which could be 33 ms, 233 ms, or 333 ms. This variant of the Flanker task is called the *temporal flanker task*, because the flankers appear prior to the target (Falkenstein, Hoormann, & Hohnsbein, 2001; Hazeltine et al., 2011).

The classic temporal flanker task has less spatial overlap between the target and distracters than do the Simon and prime-probe tasks, because a distracter does not appear at the target's location. As suggested by the spatial overlap hypothesis, this lack of overlap could enable participants to filter the peripheral distracters by focusing spatial attention more narrowly on the target's location (Eriksen & Eriksen, 1974). Since the CSE is driven by distracter processing, this lack of overlap might reduce the CSE. To investigate this possibility, we included a between-participants manipulation of whether the row of distracter letters that appeared prior to the target letter included a central distracter at the target's upcoming location. This manipulation allowed us to determine whether a CSE emerges in the temporal flanker task only when two conditions are met: (a) S-R translation can be completed more quickly for a distracter than for a target and (b) a distracter appears at the same location as the target.

Method

Participants. Two hundred seventy-two individuals participated in the study. One hundred thirty-nine participated in the task variant that did not include a distracter at fixation (48 in the 33 ms ISI condition, 46 in the 233 ms ISI condition, and 45 in the 333 ms ISI condition). One hundred thirty-three participated in the task variant that did include a distracter at fixation (45 in the 33 ms ISI condition, 45 in the 233 ms ISI condition, and 43 in the 333 ms ISI condition).

Prior to analyzing the CSE in the task variant that did not include a distracter at the target's location, several participants were excluded. Five were excluded because they failed to perform correctly on at least 70% of the trials (one from the 33 ms ISI condition, three from the 233 ms ISI condition, and one from the 333 ms ISI condition). Three more were excluded because their mean RT across all conditions was greater than 2.5 standard deviations from the group mean RT (two from the 33 ms ISI condition, zero from the 233 ms ISI condition, and one from the 333 ms ISI condition; mean RT outliers were computed separately at each ISI). Finally, one participant was excluded for having completed another ISI variant of the same task. Data from the remaining 130 individuals were employed in subsequent analyses. Of these individuals, 130 self-reported their sex (64 female, 66 male) and 124 self-reported their age (mean age, 32.14 years; age range, 19–72 years).

Prior to analyzing the CSE in the task variant that did include a distracter at the target's location, several additional participants were excluded. Twelve were excluded because they failed to perform correctly on at least 70% of the trials (two from the 33 ms ISI condition, six from the 233 ms ISI condition, and four from the 333 ms ISI condition). Three more were excluded because their mean RT across all conditions was greater than 2.5 standard deviations from the group mean RT (one from the 33 ms ISI condition, zero from the 233 ms ISI condition, and two from the 333 ms ISI condition; mean RT outliers were computed separately at each ISI). Data from the remaining 118 individuals were employed in subsequent analyses. Of these individuals, 118 self-reported their sex (54 female, 64 male) and 115 self-reported their age (mean age, 31.75 years; age range, 18–60 years).

Stimuli. The stimuli were identical to those in the Flanker task of Experiment 2 with two exceptions. First, in each trial, the distracter letters appeared before the target. Specifically, there were three sequential events: the distracter letters appeared for 133 ms, a blank screen appeared for 33 ms, 233 ms, or 333 ms, and the target letter appeared simultaneously with the peripheral distracter letters for 133 ms. Second, for some participants, a distracter letter also appeared at the target's upcoming central location. This letter was identical to the simultaneously presented peripheral distracters but, unlike those stimuli, was not presented simultaneously with the target because it occupied the same central location.

Task and Design. The task and design were identical to those specified for the Flanker task of Experiment 2 with two important exceptions (Figure 1c). First, we varied the ISI. Second, we varied the presence or absence of a central distracter letter. Both factors were varied between participants. The task instructions and practice trials for the three ISI conditions without a central distracter can be found at: https://dl.dropboxusercontent.com/u/163901707/AMT/NoCentralDistracter33/FlankerMain.html

The task instructions and practice trials for the three ISI conditions that include a central distracter can be found at: https://dl.dropboxusercontent.com/u/163901707/AMT/CentralDistracter233/FlankerMain.html

Procedure. The procedure was identical to that in Experiment 1.

Data analysis. Mean RT and mean error rate were analyzed separately with a repeated-measures ANOVA that included two within-participants factors—current congruency (congruent, incongruent) and previous congruency (congruent, incongruent)—and two between-participants factors—ISI (33 ms, 233 ms, 333 ms) and central distracter (present, absent). Averaging across all conditions, 4.34% of the trials were errors and 2.24% were outliers.

Results

Mean RT. There were four main effects. First, there was a main effect of current congruency, $F(1, 242) = 181.965$, $p < .001$, $\varsigma_p^2 = .429$, because mean RT was slower in incongruent trials (1,253 ms) than in congruent trials (1,180 ms). Second, there was a main effect of previous congruency, $F(1, 242) = 24.581$ $p = .001$, $\varsigma_p^2 = .092$, because mean RT was slower when the previous trial was incongruent (1,222 ms), relative to congruent (1,211 ms). As we mentioned in Experiment 2, this effect may index "postconflict" slowing (Ullsberger et al., 2005; Verguts et al., 2011). Third, there was a main effect of ISI, $F(2, 242) = 54.401$,

$p < .001$, $\varsigma_p^2 = .310$, because mean RT increased with ISI: mean RT was fastest at the 33 ms ISI (1,024 ms), slower at the 233 ms ISI (1,272 ms), and slowest at the 333 ms ISI (1,354 ms). Fourth, there was a main effect of central distracter, $F(1, 242) = 8.764$, $p < .005$, $\varsigma_p^2 = .035$, because mean RT was slower when a central distracter was present (1,257 ms) as compared to absent (1,177 ms).

There were also three two-way interactions. First, there was an interaction between previous congruency and central distracter, $F(1, 242) = 5.085$, $p < .05$, $\varsigma_p^2 = .021$, because the degree to which mean RT was slower when the previous trial was incongruent as compared to congruent was greater when a central distracter was present (16 ms) as compared to absent (6 ms). Second, there was an interaction between current congruency and central distracter, $F(1, 242) = 21.389$, $p < .001$, $\varsigma_p^2 = .081$, because the congruency effect was larger when a central distracter was present (98 ms) as compared to absent (48 ms). Third, there was an interaction between previous congruency and current congruency (i.e., a CSE), $F(1, 242) = 18.753$, $p < .001$, $\varsigma_p^2 = .072$, because the congruency effect was larger when the previous trial was congruent (82 ms) as compared to incongruent (63 ms). Tests of simple effects revealed that mean RT was faster in cC trials (1,170 ms) than in iC trials (1,191 ms), $F(1, 242) = 33.693$, $p < .001$, $\varsigma_p^2 = .122$, but not faster in iI trials (1,254 ms) than in cI trials (1,252 ms), $F(1, 242) < 1$.

Finally, there was a three-way interaction between previous congruency, current congruency, and central distracter, $F(1, 242) = 12.536$, $p < .001$, $\varsigma_p^2 = .049$, because the CSE was larger when a central distracter was present as compared to absent. Planned interaction contrasts revealed a significant two-way interaction between previous congruency and current congruency when a central distracter was present, $F(1, 115) = 27.021$, $p < .001$, $\varsigma_p^2 = .019$ (Figure 4a), but not when a central distracter was absent, $F(1, 127) < 1$ (Figure 4b). Tests of simple effects on the significant two-way interaction observed when a central distracter was present revealed that mean RT was faster in cC trials (1192 ms) than in iC trials (1225 ms), $F(1, 115) = 40.261$, $p < .001$, $\varsigma_p^2 = .259$, but *not* faster in iI trials (1305 ms) than in cI trials (1306 ms), $F(1, 115) < 1$. No other effects were significant.

Mean error rate. There were two main effects. First, there was a main effect of current congruency, $F(1, 242) = 5.684$, $p = .02$, $\varsigma_p^2 = .023$, because mean error rate was higher in incongruent trials (3.8%) than in congruent trials (3.2%). Second, there was a main effect of previous congruency, $F(1, 242) = 10.764$, $p = .001$, $\varsigma_p^2 = .043$, because mean error rate was lower when the previous trial was incongruent (3.3%) as compared to congruent (3.8%). Thus, it appears that there was a speed–accuracy trade-off: participants responded both more slowly and more accurately after incongruent trials than after congruent trials, consistent with "postconflict" slowing (Ullsberger et al., 2005). No other effects were significant.

Discussion

Consistent with the response modulation and spatial overlap hypotheses, we observed a robust CSE in the temporal flanker task, but only when a distracter appeared at the upcoming target's location. This result suggests that a CSE emerges in this task only when two conditions are met: (a) S-R translation can be completed more rapidly for the distracter than for the target and (b) the distracter and the target appear at the same location, thereby ensuring that spatial attention cannot be employed to filter the distracter.

The lack of a three-way interaction among ISI, previous congruency, and current congruency may appear surprising from the perspective of the activation-suppression hypothesis. However, even at the shortest, 33 ms ISI, the onset of the prime occurred 166 ms before the onset of the target. Thus, there was likely sufficient time for suppression of the distracter response to begin at this ISI before the target response became active. Critically, response suppression, as indexed by the negative-going delta plot slopes that are frequently employed to test the activation-suppression hypothesis, does not always increase uniformly when the ISI in prime-probe tasks becomes larger than about 50 ms (Burle et al., 2005,

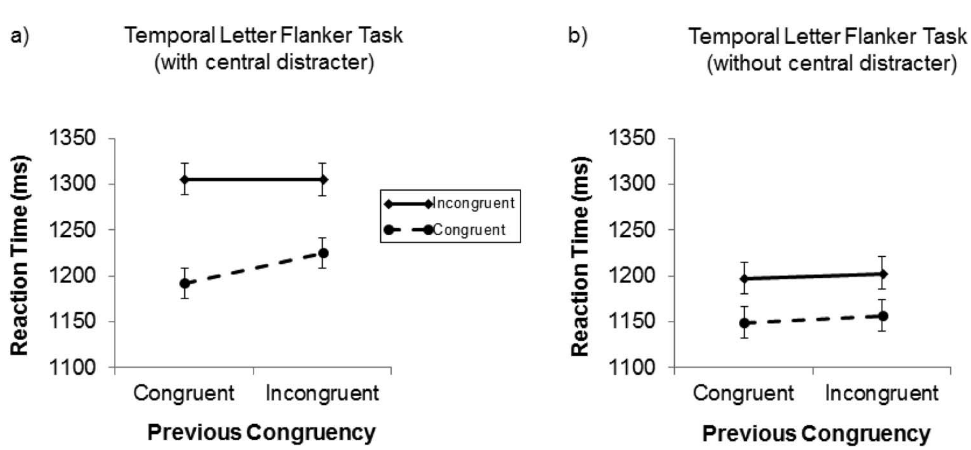

Figure 4. The congruency sequence effect in two variants of the temporal letter flanker task in Experiment 3. (a) When a distracter letter appeared at the target's upcoming location, we observed a significant congruency sequence effect. Here, cC trials were performed significantly more quickly than iC trials, but iI trials were not performed significantly more quickly cI trials. (b) When a distracter letter did not appear at the target's upcoming location, we did not observe a significant congruency sequence effect.

Experiment 1). Thus, consistent with the present results, it appears that a suppression-driven component of the CSE could remain stable across multiple ISIs.

General Discussion

In the present study, we investigated the critical task parameters that influence whether a CSE emerges in distracter interference tasks independent of feature integration and contingency learning confounds. Of importance, we observed the CSE when two conditions were met: (a) S-R translation could be completed more quickly for the distracter than for the target and (b) a distracter appeared at the same location as the target. We also found that the size of the CSE did not vary consistently with the size of the congruency effect. These findings have important implications for a literature that now routinely questions whether a CSE can be observed independent of feature integration and contingency learning confounds (Mayr et al., 2003; Mordkoff, 2012; Schmidt, 2013; Schmidt & De Houwer, 2011). They also impose some important new constraints on various cognitive control accounts of the CSE.

Two Influences on Whether a CSE can Be Observed Independent of the Typical Confounds

The first influence on whether a CSE was observed appeared to be whether S-R translation could be completed more quickly for the distracter than for the target. Specifically, we observed a CSE in the prime-probe, Simon, and temporal flanker tasks, wherein S-R translation could be completed much more rapidly for the distracter than for the target. In contrast, we did not observe a CSE in the classic Stroop or Flanker tasks, wherein S-R translation for the distracter and the target were likely completed at more similar times, relative to the other tasks. Consistent with a variant of the response modulation hypothesis—the activation-suppression hypothesis (Ridderinkhof, 2002)—these findings suggest that a CSE is more likely when S-R translation for the distracter receives a “Head Start” relative to S-R translation for the target. As such, they appear to explain why a CSE was absent in prior studies of the classic Stroop and Flanker tasks that controlled for feature integration and contingency learning confounds (Jiménez & Méndez, 2013; Mayr et al., 2003; Schmidt & De Houwer, 2011). Before a firm conclusion can be reached about whether the activation-suppression hypothesis best accounts for the CSE, however, future studies will be needed to further investigate this account and to contrast it with other variants of the response modulation hypothesis.

Future studies might also investigate whether faster S-R translation for the distracter than for the target is important for triggering increased control, applying increased control, or both. The activation-suppression hypothesis assumes that a temporal difference in response activation is important for triggering increased control, because heightened response suppression in the previous trial inhibits the entire pathway underlying selection of the distracter response in the current trial. Consistent with this possibility, the slope of the delta plot that is typically employed to measure response suppression in tests of the activation-suppression hypothesis is more negative after “partial error” trials (correctly performed trials in which the muscle corresponding to an incorrect response becomes activated) than after pure-correct trials (correct trials in which no such “incorrect” muscle activation occurs) (Burle et al., 2002). However, a temporal difference in response activation may also be important for applying increased control. For example, selective inhibition of the distracter response in the current trial may be more effective when the distracter response is more easily distinguished from the target response due to an earlier onset time. Future studies might therefore investigate whether the ability to observe a CSE depends on faster S-R translation for a distracter than for a target in the previous trial, the current trial, or both.

The second important influence on whether a CSE was observed was whether a distracter appeared at the same location as the target. This was likely a critical influence, because all of the CSEs we observed were in tasks in which a distracter appeared at the target’s location. The importance of this influence likely stems from the fact that, when a distracter appears at a location other than the target’s location, spatial attention can be employed to reduce its influence on performance (Eriksen & Eriksen, 1974). In line with this view, the congruency effect in the temporal flanker task was much larger when a distracter appeared at the target’s location than when no distracter appeared at the target’s location (i.e., 98 ms vs. 48 ms in Experiment 3).

Given that presenting a distracter at the target’s location increases the congruency effect, one might wonder whether it is the size of the congruency effect that influences whether a CSE is observed, rather than whether a distracter appears at the target’s location. However, the present data revealed no consistent relationship between the size of the congruency effect and the size of the CSE. In Experiment 2, for example, the CSE was significantly larger in the Simon task than in the Stroop task, even though the congruency effect was significantly larger in the Stroop task than in the Simon task. Thus, it appears that the size of the CSE cannot always be predicted by the size of the congruency effect.[2]

Implications of Our Findings for Current Accounts of the CSE

At the broadest level, our findings appear encouraging for the view that trial-by-trial adjustments of cognitive control contribute to the CSE. First, they show that a CSE can be observed in multiple distracter interference tasks independent of the typical feature integration and contingency learning confounds. Second, the way in which the CSE varied across different tasks and task conditions appeared most consistent with a variant of the response modulation hypothesis—the activation-suppression hypothesis (Ridderinkhof, 2002)—in which the CSE results from trial-by-trial modulations of response suppression related to distracter processing. These findings weigh in favor of the view that the CSE indexes trial-by-trial adjustments of cognitive control that modulate response-related aspects of distracter processing.

[2] This conclusion was further supported by a series of across-subject correlations indicating that CSE magnitude does not consistently correlate with the size of the congruency effect. In particular, we observed a significant correlation between these measures in the classic Stroop and Simon tasks (Stroop: $r(41) = 0.305$, $p = .047$; Simon: $r(44) = 0.429$, $p = .0029$; Experiment 2), but not in the prime-probe task ($r(41) = 0.256$, $p = .0973$; Experiment 1), classic Flanker task ($r(39) = 0.0522$, $p = .746$; Experiment 2), or temporal letter flanker task ($r(246) = 0.0935$, $p = .142$; Experiment 3).

Also important, our finding that the CSE can be dissociated from the size of the congruency effect appears to impose constraints on certain other cognitive control accounts. First, this finding does not appear to support the conflict monitoring model, in which the CSE is triggered by previous-trial response conflict (Botvinick et al., 2001; Yeung et al., 2011). In this model, RT variance in general and, hence, the difference in mean RT between incongruent and congruent trials, largely reflects trial-by-trial fluctuations of response conflict. Further, response conflict triggers the CSE. Thus, the model appears to predict that a larger congruency effect should be associated with a larger CSE. We acknowledge, however, that this prediction may be weaker when it is tested with across-task comparisons of the CSE (as in Experiment 2), because control adjustments in the model are scaled by a learning parameter that may differ across tasks (Botvinick et al., 2001). Second, it is unclear whether this finding is consistent with theories in which the CSE is driven by expectations regarding upcoming congruency (Gratton et al., 1992) or by negative affect induced by incongruent trials (Fritz & Dreisbach, 2013). To be consistent, these theories would need to posit that the process that triggers the CSE is at least somewhat independent of previous-trial RT. It is not clear, however, that these theories make this assumption. In sum, our finding that the CSE can vary independently of the congruency effect appears to place important constraints on certain cognitive control accounts.

Notably, however, this finding appears consistent with the activation-suppression hypothesis. In this view, the congruency effect indexes a variety of factors, including dimensional overlap, the efficiency of response selection, and conflict at perceptual levels (Ridderinkhof, 2002). In contrast, the CSE specifically indexes across-trial modulations of response suppression (Ridderinkhof, 2002; van Campen, et al., 2014; van den Wildenberg et al., 2010; Wylie et al., 2010).

It is important to note that our findings do not rule out the possibility that trial-by-trial adjustments of perceptual attention also contribute to the CSE (Egner & Hirsch, 2005; Polk et al., 2008; Weissman et al., 2004). However, they suggest that any such adjustments are likely to make larger contributions to the CSE when S-R translation is completed more rapidly for the distracter than for the target. Consistent with this view, we did not observe a CSE in the Stroop and Flanker tasks, wherein S-R translation for the distracter and the target likely finished at more similar times, relative to the Simon task. Also consistent, it has been suggested that deploying more and less perceptual attention to the distracter, respectively, after congruent and incongruent trials of the prime-probe task may contribute to the CSE (Hazeltine et al., 2011). Future studies could directly test this hypothesis by using cognitive neuroscience methods to investigate whether the deployment of perceptual attention to the distracter in the prime-probe task is greater after congruent trials, relative to incongruent trials.

Finally, we note that our findings appear to contradict the view that a CSE can be observed independent of the typical learning and memory confounds only when participants alternate between two S-R mappings that share a common response set (Lee & Cho, 2013). Specifically, we observed CSEs without these confounds even when participants alternated between two S-R mappings that had no responses in common. While the reasons for this discrepancy are presently unclear, Lee & Cho's experiment differed from ours in at least two important ways. First, their experiment measured across-task CSEs while ours measured within-task CSEs. Second, their experiment contained both stimulus and response repetitions while ours did not. Future research will be necessary to determine which of these, or other, methodological differences might account for the different outcomes that we and Lee & Cho observed. At present, we simply conclude that a shared response set does not appear to be necessary in order to observe a CSE independent of the typical confounds.

Implications of Our Findings for Future Studies of the CSE

By identifying the critical task parameters that determine whether a CSE is observed independent of feature integration and contingency learning processes, the present findings will aid future behavioral investigations of the psychological processes underlying the CSE. As mentioned earlier, numerous accounts of the CSE have been proposed that make no reference to either feature integration or contingency learning processes. Thus, future behavioral investigations of these accounts would likely profit greatly from the use of tasks in which the CSE is not confounded with these processes, such as the tasks described in the present article. As just one example, the size of the CSE is often different in patients with clinical disorders than in healthy controls (Kerns et al., 2005; Melcher, Falkai, & Gruber, 2008). To clarify the nature of these group differences, future research could investigate whether they are specific to distracter interference tasks that confound the CSE with feature integration and/or contingency learning processes, consistent with a learning and memory account, or appear even in tasks in which no such confounds are present, consistent with a cognitive control account.

Employing tasks in which the CSE is not confounded with feature integration and contingency learning processes will also help to clarify whether the CSE is observed when certain task parameters change across adjacent trials. Some findings suggest that observing a CSE depends on the repetition of a specific conflict type (Egner, Delano, & Hirsch, 2007; Funes, Lupianez, & Humphreys, 2010) or on participants perceiving two trials as being part of the same task (Hazeltine et al., 2011). Other results, however, suggest that a CSE can be observed even when the entire task changes across consecutive trials, if at least one of the two tasks is personally relevant (Kleiman, Hassin, & Trope, 2013). Finally, still other data suggest that an across-task CSE can be observed even when neither of the two tasks is personally relevant, consistent with a domain-general conflict resolution process (Kan et al., 2013; Kunde & Wuhr, 2006). In short, there is a general lack of agreement regarding whether the CSE can be observed when certain task parameters, or the entire task, change across trials.

It is not clear how to interpret many of these findings, however, because the CSE was often confounded with feature integration or contingency learning processes. In one of the studies mentioned above (Funes et al., 2010, Experiment 2), the authors removed cC and iI trials with exact stimulus-response repetitions but acknowledged that, according to feature integration theory, the remaining complete alternation trials in these conditions should still be performed more quickly than the partial repetition trials in the cI and iC conditions (Hommel et al., 2004). Feature repetitions effects were also not completely ruled out in two of the remaining studies mentioned above (Egner et al., 2007; Kleiman et al., 2013). Finally, in some of the above studies, each congruent stimulus was presented more often than each incongruent stimulus, raising the possibility that contingency learning processes contributed to the CSE (Hazeltine et al., 2011; Kan et al., 2013). By using tasks that do not contain such confounds, similar to those in the present article, future studies could better determine whether observing the CSE depends on the factors above. They could also determine whether the two conditions we have identified as being necessary for observing within-task CSEs are also necessary for observing across-task CSEs.

Using tasks in which the CSE is not confounded with feature integration and contingency learning processes will also facilitate future cognitive neuroscience investigations of the CSE. For example, a large number of functional neuroimaging studies have been conducted to investigate the conflict monitoring account of the CSE (Botvinick, et al., 1999; MacDonald, Cohen, Stenger, & Carter, 2000; Sheth et al., 2012). In this account, a CSE emerges when the anterior cingulate cortex (ACC) signals the presence of response conflict to the dorsolateral prefrontal cortex (DLPFC), which resolves such conflict by increasing attention to task-relevant goals and stimuli. While some findings in the literature fit with this account, they typically stem from paradigms in which the CSE could reflect feature integration and/or contingency learning processes (Schmidt, 2013). Thus, prior results that appear to implicate the ACC and DLPFC in different aspects conflict monitoring may instead indicate distinct roles for these regions in feature integration and/or contingency learning processes. Future studies that employ tasks like the ones described here could therefore be extremely useful for more accurately determining how different brain regions contribute to the CSE.

Finally, our account of the CSE makes novel predictions that could be tested in future studies. For example, our account predicts that a CSE should be observed in a vocal Stroop task wherein participants verbally identify the ink color in which a word is printed. In such a task, the vocal response engendered by the distracter word (e.g., RED!) is likely to be activated much earlier than the vocal response engendered by the target ink color (e.g., BLUE!) due to our extensive experience with reading (MacLeod, 1991). Thus, unlike for the manual Stroop task employed in the present study, our account predicts a CSE for a vocal Stroop task even when feature integration and contingency learning confounds are absent. Future studies could be conducted to investigate this and other novel predictions that derive from our account.

Limitations

The conclusions we have drawn rest upon the assumption that Internet-based data-collection methods are appropriate for psychological investigations of distracter interference tasks. As mentioned in the Introduction, prior work has suggested this is the case by showing that Internet-based studies of such tasks qualitatively replicate the results of laboratory-based studies (Crump et al., 2013; Simcox & Fiez, 2014). However, it is also important to assess whether Internet-based data collection was appropriate for the behavioral tasks we employed.

Along these lines, the present findings appear consistent with prior findings from laboratory studies in several respects. First, the results of Experiment 1 involving the prime-probe task exactly replicated our laboratory study of an identical task (Schmidt & Weissman, 2014): the main effects and interactions that were significant here were also significant in our prior study; analogously, the main effects and interactions that were not significant here were also not significant in our prior study. Second, the results of Experiment 1 conceptually replicated other findings indicating a CSE in the prime-probe task (Kunde & Wuhr, 2006). Third, the results of Experiment 2 replicated prior data indicating the absence of a CSE in the Stroop and Flanker tasks in paradigms that controlled for feature integration and contingency learning confounds (Schmidt & De Houwer, 2011). Fourth, the results of Experiment 3 replicated prior findings of "postconflict" slowing in distracter interference tasks (Ullsberger et al., 2005; Verguts et al., 2011). Given the present replications of previous laboratory studies, it appears that collecting behavioral data via AMT is highly appropriate for the distracter interference tasks we employed. For this reason, Internet-based data collection methods could prove highly useful for future studies of distracter interference tasks, especially when large amounts of data are needed to investigate a wide space of hypotheses as in the present study.

Finally, it is important to acknowledge that at least one prior study has reported higher-order CSEs across several trials (e.g., a reduced congruency effect when the stimulus three trials back was incongruent as compared to congruent) in the absence of first-order CSEs (i.e., a reduced congruency effect when the stimulus one trial back was incongruent as compared to congruent) while controlling for feature repetition and contingency learning confounds (Jiménez & Méndez, 2013). Such findings suggest that higher-order CSEs might be produced by mechanisms other than those assumed by the response modulation and spatial overlap hypotheses. Future studies should be conducted to investigate this possibility.

Conclusion

We have identified two critical variables that influence whether or not a CSE can be observed in distracter interference tasks without feature integration or contingency learning confounds. Further, the effects we have observed appear consistent with a response suppression account of the CSE. We hope that our findings will help future researchers to further investigate the psychological and neural processes that give rise to this intriguing phenomenon.

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