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An Analysis of N2 Event-Related-Potential Correlates of Sequential and Response-Facilitation Effects in Cognitive Control

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Abstract: According to conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001), sequential adjustments in cognitive control indicate that encountering information-processing conflict engages cognitive-control mechanisms. With 20 participants in an event-related-potential (ERP) experiment, we found significant congruence-sequence effects (CSEs) for behavioral measures and for N2 amplitude, a negative-going ERP component established in previous work to be related to cognitive control. We also found an interaction between the Stroop-trajectory manipulation and a response-compatibility manipulation for behavioral measures and, to a lesser extent, for N2 amplitude, such that the Stroop-trajectory congruence effect was larger on response-compatible than on response-incompatible trials. This study is the first to identify N2 amplitude as a neural correlate of the CSE in a confound-minimized task. Accordingly, these results found N2 amplitude to be associated with adjustments in cognitive control as a function of sequential and response-facilitation effects while also validating the Stroop-trajectory task as a confound-minimized means of assessing neural correlates of CSEs.

Keywords: cognitive control, N2 event-related potentials, congruence-sequence effect, information-processing conflict, Simon effect

Enacting goal-directed behavior requires alternating between automatic and controlled responding, often while concurrently monitoring multiple task goals. Cognitive control is posited to involve processing ongoing environmental and behavioral information in light of task goals (Botvinick, Braver, Barch, Carter, & Cohen, 2001). According to conflict-monitoring theory (Botvinick et al., 2001), the anterior cingulate cortex (ACC) continually monitors for information-processing conflict (as when two incompatible motor responses are initiated), facilitating context-appropriate up- or down-regulation of cognitive control (Botvinick et al., 2001). Thus, sequential adjustments in cognitive control, termed congruence-sequence effects (CSEs), are characterized by improvements in performance on the second of two high-conflict events. These sequential adjustments in cognitive control presumably occur because the second of two high-conflict events requires less effortful control, given that the needed mechanism (e.g., selective attention) of cognitive control already has been engaged (Botvinick et al., 2001). Cognitive control also is modulated through priming correct or incorrect responses (also known as response-facilitation effects), given that priming task-inappropriate responses increases information-processing conflict (Kopp, Mattler, Goertz, & Rist, 1996). A widely studied event-related-potential (ERP) component related to conflict detection and resolution is the fronto-central N2 response, typically of maximal amplitude 200–300 ms after stimulus presentation (e.g., Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). We investigated N2 amplitude and its association with adjustments in cognitive control as a function of sequential and response-facilitation effects.

Congruence-Sequence Effects and the Conflict-Monitoring Hypothesis

Numerous methodological confounds have obscured whether previous CSE findings could be explained by modulations in cognitive control or by episodic-retrieval or expectancy-based processes. Generating specific responses to specific stimuli generates episodic traces that bind perceptual and action features that guide subsequent action (Hommel, 1998, 2004). To the extent that stimulus

and response elements integrate into an event file, later activation of one element activates the other (Hommel, 2004). When exact stimulus and response elements are repeated, termed *repetition priming*, this leads to fast and accurate responding. However, when one feature is accessed (e.g., the stimulus is the same) but the other feature bindings of previous episodic traces need to be overcome (e.g., the response is different), this *partial repetition* causes slower and less accurate responding. One well-known example of a partial repetition is *negative* priming, when responding to a recently ignored stimulus causes slower and less accurate responding (e.g., Neill, Valdes, Terry, & Gorfein, 1992; Tipper, 1985), which itself can interfere with CSEs (Bugg, 2008). Also rendering previously reported CSEs difficult to interpret, removing exact-repetition trials from randomly presented cognitive-control tasks, in an effort to eliminate repetition-priming effects, introduces a confound, because partial repetitions would be more prevalent in some kinds of CSE-relevant transitions than others (Spapé & Hommel, 2014). Moreover, using cognitive-control tasks with more than two responses can introduce stimulus-contingency confounds, because each stimulus will be paired more often with its congruent response than with any other response (Schmidt & De Houwer, 2011). On the other hand, eliminating stimulus-contingency confounds in a four-response task (by using .25 congruent and .75 incongruent trials) introduces a new confound, because the nonequivalent proportions of congruent and incongruent trials would mean that some CSE-relevant trial successions occur more often than others (as discussed in Freitas & Clark, 2015).

Recent behavioral research now shows that CSEs are observed in a variety of confound-minimized tasks, providing evidence of the previously controversial effect as explained by the cognitive-control account (Duthoo, Abrahamse, Braem, & Notebaert, 2014; Freitas & Clark, 2015; Weissman, Jiang, & Egner, 2014; Schmidt & Weissman, 2014). The present study uses the Stroop-trajectory task (Freitas & Clark, 2015), a task specifically designed to minimize the aforementioned confounds in the CSE literature. In the Stroop-trajectory task, pointing triangles are presented one-at-a-time, yielding an array of slightly overlapping triangles on each trial. The goal of the task is to indicate the location of the smaller triangle that appears at either the top or the bottom of vertically oriented arrays. Trial congruence reflects whether or not the smaller triangle's location matches the direction indicated by all other triangles in the array. In the Stroop-trajectory task, unlike in traditional Flanker tasks and some Stroop tasks, participants never respond to a particular stimulus element that they have ignored, eliminating negative priming (cf. Bugg, 2008). By limiting analyses to transitions without any response repetitions, exact repetitions are eliminated without introducing any partial-repetition confounds (cf. Spapé & Hommel, 2014). By associating each stimulus array with only two possible (congruent or incongruent) responses, the task eliminates the possibility of confounding CSE variables with stimulus-contingency expectancies (cf. Schmidt & De Houwer, 2011), while holding to .5 the probability of encountering a congruent or incongruent array on any particular trial. In light of strong behavioral evidence of CSEs with this task (Feldman & Freitas, 2016; Freitas & Clark, 2015), there remains a need for research testing whether these new methods will yield evidence of CSEs in neural data, as predicted by the conflict-monitoring hypothesis. Addressing this gap was a primary goal of the present research, which also independently assessed effects of response facilitation on N2 amplitude, as described next.

Response Facilitation and N2 Amplitude

Interrupting incipient task-incompatible responses is a critical component of cognitive control. Thus, when two conflict tasks interact, one task response may prime a correct or incorrect response for the other task. Kopp and colleagues (1996) investigated selective response priming in a hybrid-flanker Go/NoGo task, using arrowheads as target and flanker stimuli correctly or incorrectly priming NoGo responses. When arrowheads primed incorrect NoGo trials (termed a specific prime, priming a specific right or left response), compared to a NoGo trials primed with octagon flankers (termed nonspecific primes, given that they don't prime a specific right or left response), specifically primed NoGo trials increased reaction time and decreased accuracy, indicating that priming the wrong response increased the need for cognitive control (Kopp et al., 1996).

Furthermore, previous research has orthogonally combined stimulus-stimulus congruency tasks (such as Stroop-like tasks) and stimulus-response spatial correspondence tasks (such as a Simon task), creating Type 7 ensembles according to Kornblum, Hasbroucq, and Osman (1990) and Kornblum, Stevens, Whipple, and Requin (1999) taxonomy. One study by De Jong, Liang, and Lauber (1994) orthogonally combined Simon and spatial-Stroop manipulations; comprising the spatial-Stroop manipulation, participants indicated (by pressing a left- or right-sided key) the vertical position of the word "High" or "Low" appearing above or below a reference point. Comprising the Simon manipulation, the words were also presented to the left or right of fixation; however, stimulus position on the horizontal plane was irrelevant to the task. The authors observed larger Stroop effects on compatible than incompatible Simon trials. Similarly, combining a flanker and Simon task yields larger flanker effects on compatible than incompatible Simon trials

(Treccani, Cubelli, Sala, & Umiltà, 2009; cf. Wendt, Kluwe, & Peters, 2006). Those results suggest that increasing stimulus-response compatibility, thereby priming the incorrect response on incongruent Stroop and flanker trials, increases information-processing conflict and the need for cognitive control. Furthermore, a recent paper using a large stimulus set (to remove contingency learning) combined different conflict tasks across five experiments (Flanker and Stroop, Simon and Flanker, Simon and Stroop) and found that the congruency effect of one task was smaller when the stimulus was incongruent for the other task (Rey-Mermet & Gade, 2016). The authors concluded that given that two conflicts are presented concurrently, the control processes induced by one conflict source affected the control processes induced by the other conflict source (Rey-Mermet & Gade, 2016). Given these clear behavioral findings across numerous experiments, there remains a need for neural evidence of the increase in cognitive control when incongruence in one task dimension is paired with congruence in a separate task dimension.

N2 Amplitude, Cognitive Control, and Conflict-Monitoring Theory

Numerous studies have examined functional distinctions among different types of N2 components, based on anterior versus posterior topographic distribution patterns. Whereas a posterior N2 component has been related to aspects of visual attention, anterior fronto-central N2 amplitude has been related to task demands for cognitive control (for review, see Folstein & van Petten, 2008). Across a variety of tasks, N2 amplitude responses appear to signify modulation of cognitive control. Studies using the Go/NoGo task, in which participants respond to specific stimuli on Go trials and withhold responding to specific stimuli on NoGo trials, found increased N2 amplitudes when overt responding is withheld (Bruin & Wijers, 2002) and when there is increased pressure to respond quickly (Jodo & Kayama, 1992). Withholding responding to target-similar (relative to target-dissimilar) nontarget stimuli is associated with increased-amplitude N2 responses (Azizian, Freitas, Parvaz, & Squires, 2006). In addition, when NoGo frequency is manipulated, infrequent Go trials are associated with increased N2 amplitudes, supporting interpreting N2 amplitude as a general marker for cognitive control rather than as pertaining only to response inhibition (Nieuwenhuis et al., 2003). In a related vein, research using a go/Go task, in which "GO" trials involved generating maximal force, again found support for the cognitive-control interpretation of the N2 (Donkers & van Boxtel, 2004). Moreover, prior research has found higher-amplitude N2 responses when infrequent NoGo trials follow Go trials than NoGo trials, presumably reflecting a reduced need to engage cognitive control anew (Feldman, Clark, & Freitas, 2015).

Using dipole modeling (Yeung, Botvinick, & Cohen, 2004) and intracranial approaches (Wang, Ulbert, Schomer, Marinkovic, & Halgren, 2005), previous research indicates that the likely generator of the N2 is the anterior cingulate cortex (ACC), a brain region located in the medial frontal cortex that appears to play a critical role detecting information-processing conflict (Botvinick et al., 2001). Given the localization and the link to cognitive control, the N2 is a good measure of cognitive control specifically in support of conflict-monitoring hypothesis.

Congruence-Sequence Effects and N2 Amplitude

Because of their good temporal resolution, ERPs are well suited to the study of the CSE. Only very recently, research investigated neuroelectric correlates of CSE using a modified prime-probe word flanker task in a confound-minimized task, finding attenuation of the N450 and increase in positivity of the SP conflict amplitude during the second of two high-conflict events indicating clear CSEs (Larson, Clayson, Kirwan, & Weissman, 2016). Given that N2 amplitude is an important marker for the increase in cognitive control and is related to ACC activation, many studies sought to investigate this component specifically for the study of CSEs, predicting improved performance and reduced N2 amplitude during the second of two-consecutive high-conflict events (e.g., Clayson & Larson, 2011a, 2011b; Feldman et al., 2015; Freitas, Banai, & Clark, 2009; Larson et al., 2016; for review, see Larson, Clayson, & Clawson, 2014). However, previous N2 studies (e.g., Feldman et al., 2015; Freitas et al., 2009; Larson & Clayson, 2011; Larson et al., 2016), although making important contributions to the study of cognitive control, were unable to isolate CSE from dimension repetitions; accordingly, their specific contributions to the study of CSEs remain unclear. As explained above, then, a neural marker of CSEs may be the attenuation of the N2 amplitude on the second of two high-conflict events and has yet to be assessed in a confound-minimized task.

Response Facilitation and N2 Amplitude

Analyses of lateralized readiness potentials (LRPs) indicate when incorrect responses are primed on a flanker task, people begin generating the wrong response, such that later, when the critical stimulus is presented, resolving conflict between correct and incorrect responses is associated with

enhanced N2 amplitude (Kopp et al., 1996). In a related vein, subliminally priming Go responses on NoGo trials increases the amplitude of the NoGo N2 (Hughes, Velmans, & De Fockert, 2009). According to conflict-monitoring theory, the ACC continually monitors information-processing conflict and then projects to the dorsolateral prefrontal cortex (dlPFC) and to the ventral lateral prefrontal cortex (vlPFC), areas thought to be involved in carrying out cognitive-control mechanisms, such that communication between the ACC and these regions can be considered to underlie a cognitive-control loop (Carter & van Veen, 2007). Facilitating task-inappropriate responses through stimulus-response compatibility, then, should increase the magnitude of stimulus-stimulus congruency effects on N2 amplitude during cognitive-control tasks, consistent with a cognitive-control interpretation of the N2.

Present Study

We investigated CSEs on N2 amplitude, the first of which we are aware in a confound-minimized task, the Stroop-trajectory task described above. To examine multiple determinants of information-processing conflict in a single study, we also included an orthogonal response-facilitation manipulation, in which we manipulated stimulus-response compatibility by requiring participants to respond with the left or right hand (to make "up" or "down" responses) to stimuli that appeared arbitrarily on the left or right side of their focus of visual attention. Extensive research indicates that although stimulus position may be task-irrelevant, responses are faster and more accurate when the position of the stimulus and response correspond (Simon, Paullin, Overmyer, & Berbaum, 1985). We predicted a CSE in the form of a significant attenuation of N2 amplitude during the second of two incongruent trials of the modified Stroop-trajectory task. We also predicted an interaction between the Stroop-trajectory manipulation and the Simon manipulation, such that the Stroop-trajectory congruence effect on N2 amplitude would be larger on Simon-compatible than on Simon-incompatible trials.

Methods

Participants

Twenty undergraduates (11 males), aged 17–36 years (M = 19.71), participated in exchange for course credit. The sample size was planned based on previous work in our laboratory with similar sample sizes and methods, including a large number of repeated measurements across trials (e.g., Feldman et al., 2015); our aim was to collect data from a minimum of 20 participants across a single academic semester. All participants indicated that they were right-hand dominant. This study was approved by the Stony Brook Institutional Review Board. All participants gave written informed consent.

Procedure

In a darkened, sound-attenuating chamber, participants sat in a large cushioned chair approximately 90 cm from the cathode ray tube monitor (Mitsubishi Diamond Pro 700; running at 75 MHz refresh rate, with 1200 × 800 pixel resolution) on which experimental stimuli were presented.

Stimuli and Task

Modified Stroop-Trajectory Task

Participants made up/down judgments using keys that varied in (task-relevant) vertical keyboard location and also in (task-irrelevant) horizontal keyboard location. The goal of the task is to respond to the location of the small gray triangle. More specifically, half of participants used the upper-left "~" key to make "up" responses and the lower-right "enter" key to make "down" responses; the remainder of participants used lower-left "Ctrl" key to make "down" responses and the upper-right "-" key to make "up" responses (see Figure 1 for trial types). Trials began with a 400-ms fixation cue (".") horizontally and vertically centered on the monitor. Following a 26.67-ms blank screen, vertical arrays of seven black triangles (each 83 pixels high × 27 pixels wide) were either to the right or to the left of the fixation cue. Comprising the Simon manipulation, trials were coded response-compatible when the left/right location of participants' response key corresponded to the left/right location of the stimulus array and as response-incompatible when the left/right location of participants' response key did not correspond to the left/right location of the stimulus array.

Comprising the Stroop-trajectory manipulation, for upward-pointing arrays, a single upward-pointing triangle first was presented toward the bottom of the screen. In successive intervals of 26.67 ms, five other identical triangles were added to the array, with each triangle appearing immediately above the one presented before it. Finally, 40 ms after the sixth black triangle in the array was visible, the seventh identical triangle appeared immediately above the others, and a smaller (24 pixels high × 14 pixels wide) upward-pointing gray triangle appeared inside either the top black triangle (on congruent trials) or the bottom black

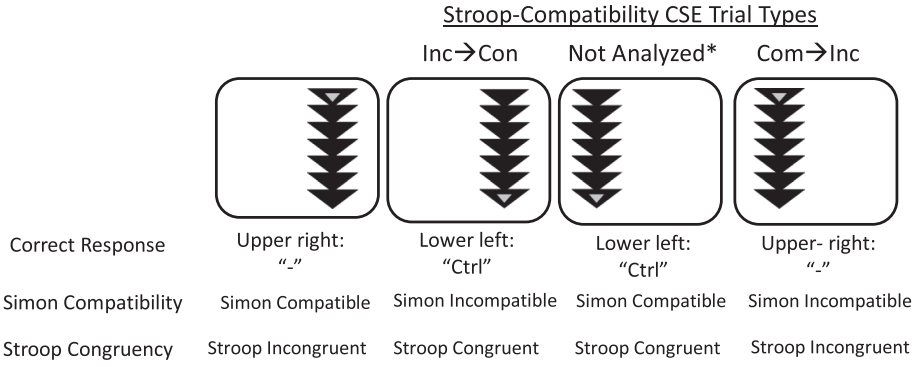

Figure 1. Illustrative trial types for participants responding to the location of the small gray triangle on the bottom of the stack with a "Ctrl" button press (lower left on keyboard) and responding to the small gray triangle on the top of the stack with a "-" button press (upper right on keyboard). Randomized trial presentations yielded orthogonal manipulation of whether or not the button press was applied across trials n and $n - 1$. *Congruence-sequence effects (CSEs) were not analyzed for any trial pairs that included response repetitions across trials n and $n - 1$.

triangle (on incongruent trials) and was presented for 146.67 ms, after which the screen remained blank as the program awaited the participant's response. For downward-pointing arrays, a single downward-pointing triangle first was presented. In successive intervals of 26.67 ms, five other identical triangles were added to the array, with each triangle appearing immediately below the one presented before it. Finally, 40 ms after the sixth black triangle in the array was visible, the seventh identical triangle appeared immediately below the others, and a smaller (24 pixels high × 14 pixels wide) downward-pointing gray triangle appeared inside either the bottom black triangle (on congruent trials) or the top black triangle (on incongruent trials) and was presented for 146.67 ms, after which the screen remained blank as the program awaited the participant's response.

Trials were separated by an interval varying randomly between 125 and 250 ms. Participants performed a computer-administered 24-trial practice block and then eight blocks of 100 trials each. Within each of the eight experimental blocks, every 25 trials (out of the 100) participants were given a break to blink. Including practice trials, experimental trials, and breaks, the experiment lasted approximately 35 min. There were equivalent proportions of the four general trial types reflecting the 2 (Stroop-trajectory: Congruent vs. Incongruent) × 2 (Simon: Compatible vs. Incompatible) manipulations. All trial types were selected for presentation randomly with replacement. To remove exact trial repetitions without creating any confounds, we excluded from all analyses trial combinations in which the same responses were required at trial n as at trial $n - 1$. This approach precludes the possibility of any imbalance in partial repetitions (of the same response to different stimuli across successive trials) as a function of Stroop-trajectory congruence at trials n and $n - 1$.

Electrophysiological Recording

The electroencephalogram (EEG) was recorded continuously via a 32-channel electrode cap (Compumedics Neuroscan Inc., Charlotte, NC) using a frontal-central electrode as ground and electrically linked mastoid electrodes as reference. The horizontal electrooculogram (EOG) was monitored from electrodes at the outer canthi of the eyes, and the vertical EOG was monitored from electrodes above and below the orbital region of the left eye. Electrode impedance was maintained below 10 kΩ for all electrodes. EEG and EOG signals were digitized at 500 Hz and amplified with a gain of 1,000 with a filter bandpass of 0.01–30 Hz.

ERP Analysis

Results are drawn from epochs beginning 100 ms before each stimulus was presented and concluding 900 ms thereafter. Baseline mean amplitude during the first 100 ms of each epoch was subtracted from remaining time points. To address EEG artifact, independent component analysis (ICA), accomplished via the Runica function of EEGlab (Delorme & Makeig, 2004), was used in two steps. First, through an initial ICA, epochs containing extreme non-stereotypic artifacts were identified and removed (11.28% of all trials). Via a second ICA, components reflecting vertical and horizontal eye movements, muscle-related activity, and channel-specific line noise were identified and subtracted. Following ICA-based corrections, any epochs with EEG voltage exceeding ±75 μV were removed, resulting in exclusion of 2.68% of remaining trials. The first trial of each block and trials following the brief rests provided within each block necessarily were not included in averages of the four possible trial $n - 1$ × trial n combinations, nor were trials on which errors were committed or trials immediately

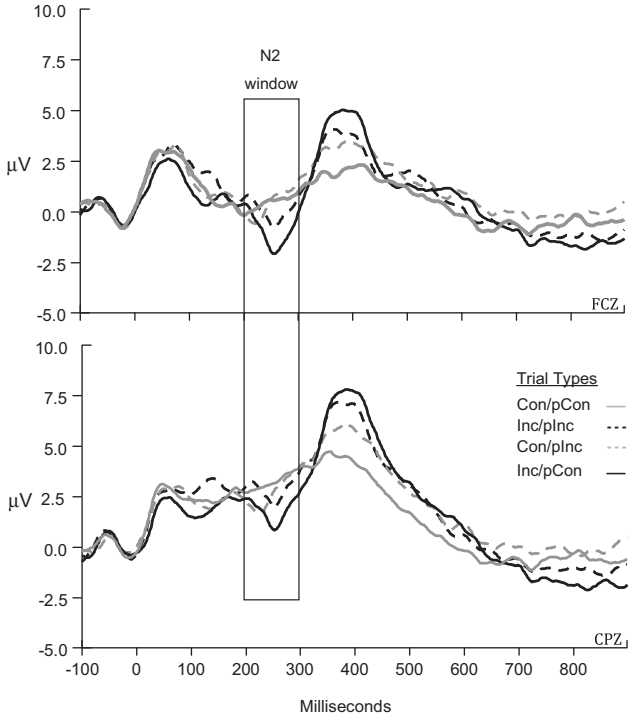

Figure 2. Grand-averaged event-related potentials as a function of the congruence status of Stroop-trajectory trials $n \times n - 1$. "Con" and "Inc" refer to congruent and incongruent. "pCon" refers to congruent trial $n - 1$ and "pInc" refers to incongruent trial $n - 1$.

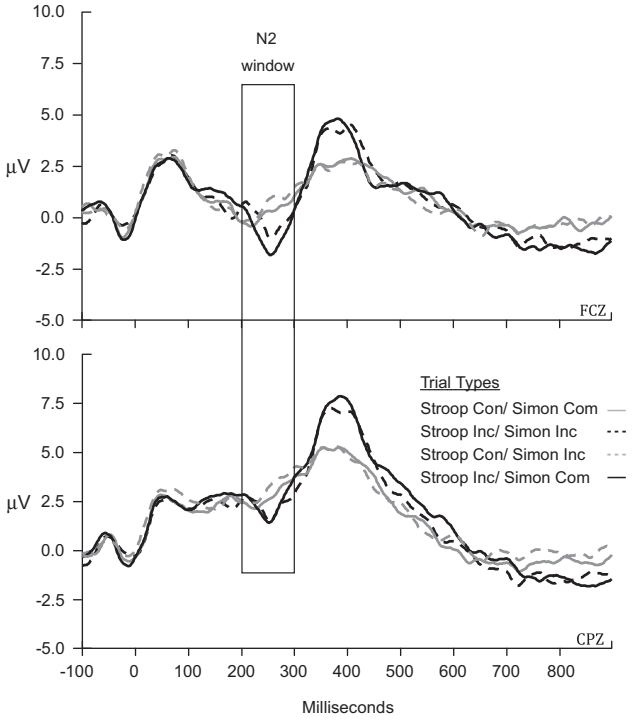

Figure 3. Grand-averaged event-related potentials as a function of the Stroop-trajectory congruence status by Simon trial compatibility status combinations. Stroop Con = Stroop Congruent; Stroop Inc = Stroop Incongruent; Simon Com = Simon Compatible; Simon Inc = Simon Incompatible.

following error trials. For each of the four possible trial $n - 1 \times$ trial n combinations (as displayed in Figure 2), there were at least 47 and at most 123 epochs (*Mdn* = 71.5) per participant; for each of the Simon trial n compatibility $\times$ Stroop-trajectory trial n congruence combinations (as displayed in Figure 3), there were at least 48 and at most 125 epochs (*Mdn* = 74.5) per participant. Given extensive evidence that N2 effects are most prominent at midline electrodes, ERP analyses were based on amplitude measurements from electrodes Fz, FCz, Cz, CPz, and Pz. Based on visual inspection of the overall waveforms (see Figures 2 and 3), N2 amplitude was defined as the mean amplitude between 200 and 300 ms. Greenhouse-Geisser-corrected p values are reported for all comparisons with more than two within-subject levels (Greenhouse & Geisser, 1959).

Results

Behavioral Congruence-Sequence Effects

For response times, using a 2 (Stroop-Trajectory Trial n: congruent or incongruent) $\times$ 2 (Stroop-Trajectory Trial $n - 1$: congruent or incongruent) analysis of variance (ANOVA), there was a significant effect of Stroop-trajectory trial n congruence, $F(1, 19) = 80.39$, $p < .0001$, $\eta^2_p = .81$, and no significant effect of Stroop-trajectory trial $n - 1$ congruence, $F(1, 19) = 3.86$, $p = .06$, $\eta^2_p = .17$. Indicating the presence of a robust CSE, the Stroop-Trajectory Trial $n \times$ Stroop-Trajectory Trial $n - 1$ congruence interaction was significant, $F(1, 19) = 15.73$, $p < .0008$, $\eta^2_p = .45$. Average proportions of correct responses also were analyzed in a 2 (Congruency Status of Trial $n - 1$) $\times$ 2 (Congruency of Trial n) repeated-measures ANOVA. For accuracy rates, there was a significant effect of Stroop-trajectory trial n, $F(1, 19) = 26.08$, $p < .0001$, $\eta^2_p = .58$, and of Stroop-trajectory trial $n - 1$ congruence, $F(1, 19) = 22.68$, $p < .0001$, $\eta^2_p = .54$. Indicating the presence of a robust CSE, the Stroop-Trajectory Trial $n \times$ Stroop-Trajectory Trial $n - 1$ congruence interaction was significant, $F(1, 19) = 35.74$, $p < .0001$, $\eta^2_p = .65$. As shown in Figure 4, encountering an incongruent cue at trial $n - 1$ significantly increased accuracy and decreased response time on incongruent relative to congruent trials, despite the absence of stimulus repetitions or of any stimulus-contingency confounds (see Table 1 for means and standard deviations).

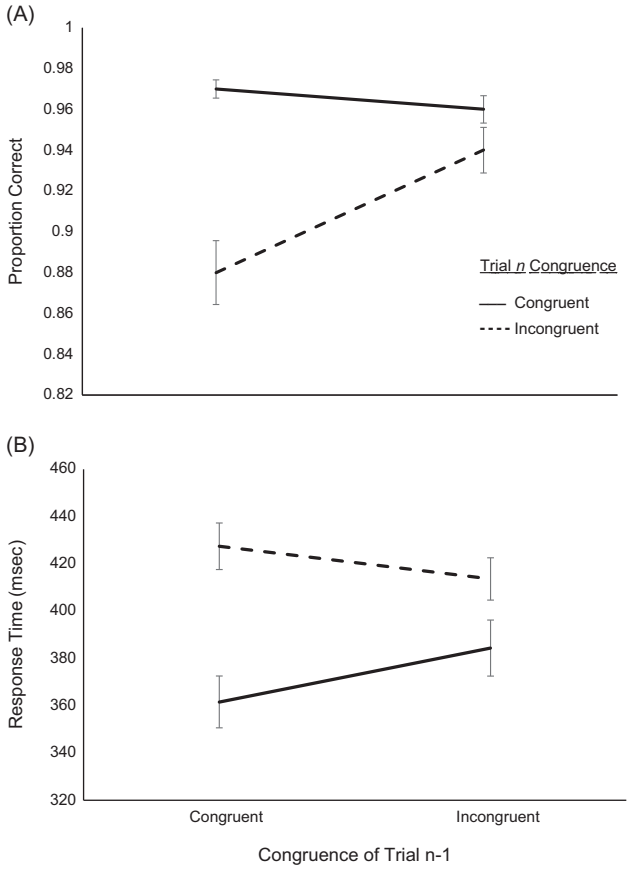

Figure 4. Congruence-sequence effects on mean accuracy (A) and mean response time in ms (B), on the Stroop-trajectory task. Error bars represent ±1 *SE* of the mean.

Congruence-Sequence Effect in N2 Amplitude

Mean amplitudes during the N2 measurement window were analyzed in a 2 (Stroop-Trajectory Trial *n*: congruent or incongruent) × 2 (Stroop-Trajectory Trial *n* − 1: congruent or incongruent) × 5 (Electrode Location) ANOVA. This analysis revealed a main effect of Stroop-trajectory trial *n* congruence, $F(1, 19) = 9.81$, $p < .01$, $\eta^2_p = .34$, reflecting a negative deflection on incongruent relative to congruent trials. Apart from a main effect of electrode location, $F(4, 76) = 14.09$, $p < .0001$, $\eta^2_p = .43$, no other main effects were significant. Most importantly, there was a significant interaction between Stroop-Trajectory Trial *n* Congruence × Stroop-Trajectory Trial *n* − 1 Congruence, $F(1, 19) = 6.22$, $p < .03$, $\eta^2_p = .25$, which did not further interact with electrode location, given that the three-way Stroop-Trajectory Trial *n* Congruence × Stroop-Trajectory Trial *n* − 1 Congruence × Electrode Location interaction was not significant statistically, $F(4, 76) = 1.19$, $p = .31$, $\eta^2_p = .06$. As indicated in Table 2, encountering an incongruent Stroop-trajectory cue at trial *n* − 1 significantly decreased the negativity of N2 amplitude on Stroop-trajectory incongruent trials at electrodes Cz, CPz, and Pz.

Simon Compatibility by Stroop-Trajectory Congruence Behavioral Results

For response times, using a 2 (Stroop-Trajectory Trial *n*: congruent or incongruent) × 2 (Simon Trial *n*: compatible

Table 1. Mean response times and proportion of correct responses for trial combinations

		Stroop-trajectory trial *n* − 1 congruence		Simon trial *n* compatibility	
Stroop-trajectory Trial *n* Congruence		Congruent	Incongruent	Compatible	Incompatible
Congruent	RT	361.60 (49.00)	384.37 (53.00)	360.67 (51.00)	385.66 (52.00)
Incongruent	RT	427.42 (44.00)	413.60 (40.00)	431.11 (45.00)	410.74 (40.00)
Congruent	Cor	0.97 (0.02)	0.96 (0.03)	0.98 (0.02)	0.96 (0.03)
Incongruent	Cor	0.88 (0.07)	0.94 (0.05)	0.88 (0.07)	0.93 (0.05)

Notes. $N = 20$. Standard deviations in parentheses. RT = response time (ms); Cor = proportion correct.

Table 2. Mean N2 amplitude on congruent and incongruent Stroop-trajectory trials, reported as a function of *n* − 1 trial type (congruent and incongruent)

	Incongruent			Congruent		
Electrode	pCon	pInc	Difference	pCon	pInc	Difference
Fz	−1.44 (3.06)	−0.96 (3.78)	0.48 (2.31)	0.34 (2.90)	−0.20 (2.70)	−0.53 (1.88)
FCz	−1.11 (3.26)	−0.12 (4.09)	1.00 (2.33)	0.71 (3.65)	0.44 (3.00)	−0.27 (2.11)
Cz	0.70 (3.60)	1.56 (4.38)	0.87 (1.88)*	2.55 (4.24)	2.07 (3.66)	−0.49 (2.08)
CPz	1.88 (3.35)	2.94 (3.93)	1.06 (1.61)**	3.70 (4.11)	2.95 (3.45)	−0.75 (1.88)
Pz	1.62 (3.05)	2.41 (3.28)	0.79 (1.50)*	3.33 (3.54)	2.57 (2.94)	−0.76 (1.68)

Notes. $N = 20$. Standard deviations in parentheses. pCon = congruent trial *n* − 1; pInc = incongruent trial *n* − 1. *$p < .05$; **$p < .01$.

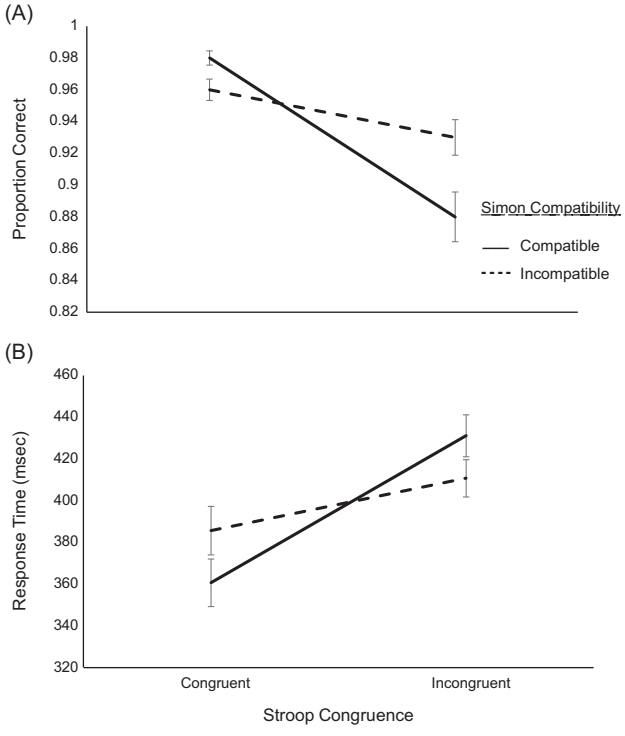

Figure 5. Simon trial compatibility by Stroop-trajectory trial congruence on mean accuracy (A) and mean response time in ms (B). Error bars represent ±1 *SE* of the mean.

or incompatible) ANOVA, there was a significant effect of Stroop-trajectory trial *n* congruence, $F(1, 19) = 81.33$, $p < .0001$, $\eta^2_p = .81$, and no significant Simon trial *n* compatibility, $F(1, 19) = 1.00$, $p = .33$, $\eta^2_p = .05$. Importantly, the Stroop-Trajectory Trial *n* Congruence × Simon Trial *n* Compatibility interaction was significant, $F(1, 19) = 29.14$, $p < .0001$, $\eta^2_p = .61$. Clarifying the nature of this interaction, as shown in Figure 5 (see also Table 1), the Stroop-trajectory interference effects were larger on compatible Simon trials than on incompatible Simon trials. Average proportions of correct responses also were analyzed in a 2 (Stroop-Trajectory Congruency Status of Trial *n*) × 2 (Simon Compatibility Status of Trial *n*) repeated-measures ANOVA. For accuracy rates, there was a significant effect of Stroop-trajectory trial *n* congruence, $F(1, 19) = 27.03$, $p < .0001$, $\eta^2_p = .59$, and no significant Simon trial *n* compatibility, $F(1, 19) = 2.76$, $p = .11$, $\eta^2_p = .13$. Importantly, the Stroop-Trajectory Trial *n* Congruence × Trial *n* Simon Compatibility interaction again was significant, $F(1, 19) = 28.08$, $p < .0001$, $\eta^2_p = .60$. Clarifying the nature of this interaction, as shown in Figure 5 (see also Table 1), the Stroop-trajectory interference effects were larger on compatible Simon trials than on incompatible Simon trials.

Simon Compatibility by Stroop-Trajectory Congruence N2 Amplitude Results

Mean amplitudes during the N2 measurement window were analyzed in a 2 (Stroop-Trajectory Trial *n*: congruent or incongruent effect) × 2 (Simon Trial *n*: compatible or incompatible) × 5 (Electrode Location) ANOVA. This analysis revealed a main effect of Stroop-trajectory trial *n* congruence, $F(1, 19) = 8.37$, $p < .01$, $\eta^2_p = .31$, reflecting a negative deflection on incongruent relative to congruent trials. Apart from a main effect of electrode location, $F(4, 76) = 14.10$, $p < .0001$, $\eta^2_p = .43$, no other main effects were significant. Contrary to our predictions, the two-way Stroop Congruency × Simon interaction was not significant, $F(1, 19) = 1.68$, $p = .21$, $\eta^2_p = .08$; the three-way interaction between Stroop-trajectory trial *n* congruence, Simon trial *n* compatibility, and electrode location also lay outside conventional levels of statistical significance, $F(4, 76) = 3.17$, $p = .053$, $\eta^2_p = .14$. As shown in Table 3, support for our prediction of increased negativity of N2 amplitude on Simon-compatible/incongruent Stroop-trajectory trials than on Simon-incompatible/incongruent Stroop-trajectory trials was evident only at electrode FCz (see Table 3).

Discussion

These findings make several contributions to current understandings of cognitive control and its neuroelectric

Table 3. Mean N2 amplitude on congruent and incongruent Stroop-trajectory trials, reported as a function of Simon trial n type (compatible and incompatible)

	Incongruent Stroop			Congruent Stroop		
Electrode	Com	Inc	Difference	Com	Inc	Difference
Fz	−1.43 (3.43)	−0.92 (3.24)	0.51 (1.45)	0.19 (2.84)	−0.11 (2.77)	−0.30 (1.80)
FCz	−0.95 (3.70)	−0.23 (3.50)	0.71 (1.52)*	0.70 (3.42)	0.39 (3.26)	−0.30 (2.01)
Cz	1.05 (4.20)	1.25 (3.72)	0.21 (1.30)	2.41 (4.08)	2.15 (3.84)	−0.26 (2.10)
CPz	2.47 (3.97)	2.39 (3.27)	−0.08 (1.18)	3.50 (3.94)	3.08 (3.59)	−0.41 (1.99)
Pz	2.01 (3.53)	2.05 (2.79)	0.04 (1.43)	3.15 (3.42)	2.70 (3.03)	−0.45 (2.00)

Notes. $N = 20$. Standard deviations in parentheses. Com = compatible; Inc = incompatible. *$p < .05$.

correlates. Our investigation of N2 amplitude followed from previous research indicating that N2 amplitude can be considered a valuable index for detecting the recruitment of cognitive control. Supporting previous work on the role of the N2 in conflict detection and resolution (e.g., Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003), we found N2 amplitude to be modulated by the Stroop-trajectory manipulation in a main effect, such that the apparent recruitment of cognitive control (on Stroop-trajectory-incongruent relative to Stroop-trajectory-congruent trials) was associated with enhanced N2 amplitude in this relatively newly developed cognitive-control task. Most importantly, our sequential N2 analysis supported the conflict-adaptation prediction of an attenuation of the N2 response on the second of two-consecutive incongruent Stroop-trajectory trials. The presently observed effect size for the CSE, in the metric of Cohen's *d*, was 0.74 at electrode CPz (where this effect was most prominent). Using this estimate as a guide for future work, attempts to replicate this effect, assuming statistical power of .80 and $\alpha = .05$, will require an *N* of 17 experimental participants.

Importantly, a recent study investigated the Stroop N450, a negative-going component peaking approximately 450 ms after stimulus presentation, as well as a slow-wave potential (conflict SP), a centroparietal positivity beginning approximately 600 ms after the stimulus presentation, to investigate the time course of the CSE in a new confound-minimized task (Larson et al., 2016). Using a modified prime-probe word flanker task (Schmidt & Weissman, 2014), they found an attenuation of the N450 and increase in positivity of the SP conflict amplitude during the second of two high-conflict events indicating CSEs (Larson et al., 2016). Importantly, the N450 is a fronto-central component thought to be similar in functionality to the N2. However, the vast preponderance of ERP research on cognitive control has focused on the N2 rather than the N450, given that the N2 occurs earlier and is less dependent on elaborated semantic processing than the N450 is (for review of conflict-related ERPs see Larson et al., 2014). Given the extensive body of research on cognitive control and the N2, a vital test of CSE as a function of cognitive control is whether N2 amplitude will be attenuated on the second of two high-conflict trials of a confound-minimized task.

Given how well studied this effect has been, it is important to note that this is the first study of which we are aware to investigate sequential modulation of N2 amplitude in a confound-minimized task; we found robust CSEs on N2 amplitude that cannot be explained by alternative accounts grounded in repetition priming (Mayr, Awh, & Laurey, 2003), episodic-memory effects (Hommel, 2004), or expectancy-based contingencies (Schmidt & De Houwer, 2011). Consequently, the present study helps identify the N2 as a neural correlate of CSEs, which previous research has been unable to do conclusively (cf. Feldman et al., 2015; Freitas et al., 2009; Larson & Clayson, 2011; Larson et al., 2016; Rustamov et al., 2013).

Importantly, although the present study found results broadly consistent with the conflict-monitoring hypothesis, we did find a more parietal N2 than expected. Given this surprisingly posterior distribution, further work will be needed to evaluate the relation of these results to work on the conflict-monitoring hypothesis. Previous research using visual oddball tasks and visual search tasks has found apparently attention-related N2 components with posterior scalp distributions (for review, see Folstein & van Petten, 2008). Accordingly, further work will be needed to assess the extent to which the present results reflect modulation of attentional control more specifically, relative to cognitive control more generally.

Turning to our investigation of the potential interaction between the Simon and Stroop-trajectory manipulations, we found clear support for our predictions in the response time and accuracy data, such that interference effects of the Stroop-trajectory manipulation were much larger on Simon-compatible trials than on Simon-incompatible trials, consistent with previous behavioral research (De Jong et al., 1994). Although significant only at FCz, we did find some support for moderation of N2 amplitude as a function of the interaction between the Simon and Stroop-trajectory manipulations. In light of this limited topographical distribution (e.g., most fronto-central N2 effects are evident at not only FCz but also Cz; Folstein & van Petten, 2008), we advocate caution in interpreting this result until it can be replicated with a larger sample. More specifically, the presently observed effect size for the Simon × Stroop-Trajectory interaction at electrode FCz, in the metric of Cohen's *d*, was 0.43. Using this estimate as a guide for future work, future work seeking to replicate this effect, assuming desired statistical power of .80 and $\alpha = .05$, will require an *N* of 43 experimental participants.

Future research also may examine whether modifying the presently used Simon manipulation, to increase its potency, may reveal a more robust electrophysiological effect. More specifically, decreasing the amount of time that elapses between initial and response-contingent cues on each trial has been found in previous research to elicit a stronger Simon effect (Hommel, 1997). Accordingly, the presently used Stroop-trajectory manipulation, by requiring a cumulative buildup of stimulus elements on each trial, does not appear optimal for detecting main effects of Simon manipulations, whereas our behavioral data did provide strong evidence that the two manipulations interacted to affect response time and accuracy. Further investigations of effects on N2 amplitude of interactions between

response-compatibility manipulations and stimulus-stimulus congruence manipulations may benefit from using response-compatibility manipulations that yield clearer main effects (cf. Wendt et al., 2006).

Conclusion

We sequentially manipulated the presentation of Stroop-trajectory task arrays such that participants responded to randomized incongruent and congruent trial arrays that were placed randomly to the right or left of the fixation point (comprising a Simon manipulation). Analyses of response times, accuracy, and event-related potentials (N2 amplitude) all yielded results indicating that participants adapted to information-processing conflict when two incongruent Stroop-trajectory trials occurred consecutively. For behavioral measures and N2 amplitude (only significant at FCz), we also found an interaction between the Stroop-trajectory manipulation and a response-compatibility manipulation, such that the Stroop-trajectory congruence effect was larger on response-compatible than on response-incompatible trials. Most importantly, our findings support interpreting the N2 as a neural correlate of the CSE and indicate that the Stroop-trajectory task can serve as a useful tool to measure CSEs absent of interpretational confounds.

Ethics and Disclosure Statements

All participants of the study provided written informed consent and the study was approved by the Stony Brook University Institutional Review Board.

The authors disclose no actual or potential conflicts of interest including any financial, personal, or other relationships with other people or organizations that could inappropriately influence (bias) their work.

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