

# ERP evidence for conflict in contingency learning

Peter S. Whitehead<sup>1</sup> | Gene A. Brewer<sup>2</sup> | Chris Blais<sup>2</sup>

<sup>1</sup>Center for Cognitive Neuroscience, Duke University, Durham, North Carolina

<sup>2</sup>Department of Psychology, Arizona State University, Tempe, Arizona

## Correspondence

Chris Blais, Department of Psychology, Arizona State University, Tempe, AZ 85287, USA.

Email: chris.blais@gmail.com

## Abstract

The proportion congruency effect refers to the observation that the magnitude of the Stroop effect increases as the proportion of congruent trials in a block increases. Contemporary work shows that proportion effects can be driven by both context and individual items, and are referred to as context-specific proportion congruency (CSPC) and item-specific proportion congruency (ISPC) effects, respectively. The conflict-modulated Hebbian learning account posits that these effects manifest from the same mechanism, while the parallel episodic processing model posits that the ISPC can occur by simple associative learning. Our prior work showed that the neural correlates of the CSPC is an N2 over frontocentral electrode sites approximately 300 ms after stimulus onset that predicts behavioral performance. There is strong consensus in the field that this N2 signal is associated with conflict detection in the medial frontal cortex. The experiment reported here assesses whether the same qualitative electrophysiological pattern of results holds for the ISPC. We find that the spatial topography of the N2 is similar but slightly delayed with a peak onset of approximately 300 ms after stimulus onset. We argue that this provides strong evidence that a single common mechanism—conflict-modulated Hebbian learning—drives both the ISPC and CSPC.

## KEYWORDS

associative learning, conflict-modulated Hebbian-learning, ERP, response conflict, Simon

## 1 | INTRODUCTION

The item-specific proportion congruency effect (ISPC; Jacoby, Lindsay, & Hessels, 2003) is used to measure cognitive control. The ISPC refers to the observation that the size of the Stroop effect can be modulated by the proportion of congruent trials for specific sets of items. For example, within a single block of intermixed trials, if the words blue and green are mostly incongruent and the words red and yellow are mostly congruent, the size of the Stroop effect for the mostly congruent items will be larger than for the mostly incongruent items. This effect is explained by the conflict-modulated Hebbian learning account (Blais, Robidoux, Risko, & Besner, 2007; Blais & Verguts, 2012; Verguts & Notebaert, 2008), which assumes that conflict-mediated stimulus-response learning elicited directly by the item mediates how much the color is attended to (and/or the word is sup-

pressed) for each item within the experiment. However, this is not the only account of the ISPC.

The parallel episodic processing model (PEP) argues that the ISPC can be explained solely by bottom-up components such as simple-stimulus response learning (Schmidt, 2013b). These lower-level components are necessary to explain nearly all cognitive control effects (Egner, 2014; Hommel, 2004; Mayr, Awh, & Laurey, 2003; Schmidt & De Houwer, 2011). Some have even claimed that low-level stimulus qualities such as feature repetitions and the contingency between the color and the word are sufficient to explain all cognitive control effects, even the namesake of the conflict monitoring hypothesis (Botvinick, Braver, Barch, Carter, & Cohen, 2001), the so-called conflict-adaptation effect (e.g., Mayr et al., 2003; Schmidt and De Houwer, 2011; but see Ullsperger, Bylsma, & Botvinick, 2005, and Blais, Stefanidi, & Brewer, 2014, respectively).

These and other such findings have led Schmidt and colleagues (Schmidt & Besner, 2008; Schmidt, Crump, Cheesman, & Besner, 2007) to argue that proportion congruency effects and sequential congruency effects have nothing to do with conflict adaptation and everything to do with contingency learning—a more general, low-level variation of stimulus-response learning mediated by episodic memory. The PEP (Schmidt, 2013b) posits that memory storage and retrieval processes for episodic memories for each of the trials occurring in the experiment are sufficient to explain the so-called control that the proportion congruency effect measures. To support their account that contingency learning is independent from control systems and does not act in reaction to response conflict, Schmidt and Besner (2008) reanalyzed the ISPC effect from Jacoby et al. (2003) and showed that response conflict and contingency yielded additive factors (cf. Sternberg, 1969) consistent with the idea of two distinct processing systems. In further support of this idea, Schmidt et al. (2007) demonstrated the presence of an ISPC effect using neutral words (Schmidt, 2013b; see also Schmidt & Besner, 2008). From this behavioral demonstration, they conclude that conflict is absent in the production of the ISPC effect, as neutral words do not require top-down control processes that would be recruited in traditional control experiments, such as the Stroop task when presented with the word RED in the color blue. Recently, Schmidt, De Houwer, & Rothermund (2016) proposed an updated computational framework for the episodic memory-based PEP model. This model hinges around two central points: (1) although response conflict occurs in the model, it does not influence the associations/learning of any stimulus-response bindings, and (2) the role of the episodic learning process is accentuated in the production of cognitive control effects. The underlying architecture of this model is based on the Collins and Loftus (1975) and Hintzman (1984) episodic memory frameworks. In contrast, the architecture of conflict-modulated Hebbian learning theories are based on the McClelland and Rumelhart (1981) and Rumelhart and McClelland (1982) interactive activation models and the Cohen, Dunbar, and McClelland (1990) strength of association framework. These underlying theoretical differences cause contention of the former point—the lack of conflict in control effects.

While these experiments and subsequent computational models show the undeniable role of stimulus-response learning in the ISPC effect, they do not show a lack of control in the production of the ISPC but simply that control-like effects can be produced under different experimental circumstances. The PEP model provides a sufficient behavioral account of the ISPC, but due to its specificity it is limited in its ability to explain other conceptually and procedurally similar findings such as the context-specific sequential congruency (CSPC) effect (see Blais, Hubbard, & Mangun, 2016;

Whitehead, Brewer, Patwary, & Blais, 2016). Hybrid models of the conflict-monitoring hypothesis, such as the conflict-modulated Hebbian learning model (i.e., Blais et al., 2007; Blais & Verguts, 2012; Verguts & Notebaert, 2008), posit that control is adjusted on an item-by-item basis—highlighting the bottom-up associative learning processes of control—while dorsolateral prefrontal cortex (DLPFC) is triggered by the “need for control” and provides top-down adjustments to performance. This hybrid model builds on the influential conflict-monitoring hypothesis (Botvinick et al., 2001), which states that response conflict is detected by the anterior cingulate cortex (ACC), which recruits executive functions residing in the DLPFC. Evidence from EEG further supports this, demonstrating an N2 ERP component, peaking at 300 ms and maximal over the midline central scalp consistent with the generation of a response conflict signal from the ACC and recruitment of executive functions in the DLPFC (Folstein & Van Petten, 2008; Van Veen & Carter, 2002). Van Veen and Carter show the N2 component’s connection to response conflict by conducting a variant of the flanker task in which they could disassociate stimulus conflict (conceptual conflict that occurs at the level of stimulus encoding; see van Veen, Cohen, Botvinick, Stenger, & Carter, 2001; Zhang, Zhang, & Kornblum, 1999) from response conflict, finding that response conflict, not stimulus conflict, was associated with an N2 over the frontocentral electrode sites. Further, the N2 has been shown to be a reliable measure of conflict adaptation (Clayson & Larson, 2013). These executive functions (i.e., Miller & Cohen, 2001) optimize goal-directed performance by adjusting (cf. Desimone & Duncan, 1995) behavioral responses.

Other accounts propose that top-down and bottom-up processes operate on a continuous hierarchy (Egner, 2014). This hierarchy is composed of multiple levels, with concrete, bottom-up processes mediating the relationship between stimulus features and response option and abstract, and top-down processes mediating generalizable task demands and difficulty. These multiple levels are encoded into an event file in memory (Hommel, 1998), which is then triggered by the stimulus, and the event file is retrieved from memory. Whether bottom-up or top-down processes mediate the response to the stimulus is controlled by a preferential system, processing the stimulus on the most concrete level needed to make an accurate response. Accounts such as the dual-item specific monitoring (dual-ISM; Bugg, 2015) specifically conceptualize the relative contributions of bottom-up and top-down processes as controlled by the salience of the irrelevant dimension (i.e., the word in a Stroop task) versus the relevant dimension (i.e., color).

To summarize, there is universal consensus that stimulus-response learning is necessary to produce an ISPC (Bugg, Jacoby, & Toth, 2008; Crump, Gong, & Milliken, 2006; Crump & Milliken, 2009; Crump, Vaquero, &

Milliken, 2008; Schmidt et al., 2007; Schouppe, de Ferrere, Van Opstal, Braem, & Notebaert, 2014; Shedden, Milliken, Watter, & Monteiro, 2013). However, Schmidt's (2013a) demonstration of an ISPC and sequential congruency effects (e.g., Gratton, Coles, & Donchin, 1992) in the absence of conflict questions the need to appeal to conflict adaption. We assess this hypothesis here by measuring the neural response that occurs in an ISPC task with the goal of determining whether the N2—an ERP component known to be sensitive to response conflict—differs as a function of mostly congruent versus mostly incongruent items. The N2 component is an ERP waveform that peaks over the midline central scalp (i.e., electrode Fz) approximately 300 ms following the onset of the stimulus. Its presence is thought to reflect the engagement of cognitive conflict (Bartholow et al., 2005; Folstein & Van Petten, 2008; Van Veen & Carter, 2002) and purported to be generated from the dorsal ACC, a region which fMRI studies have identified as activated during response conflict (Carter et al., 1998; Carter & van Veen, 2007; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000). Blais et al. (2016) showed that the N2 is associated with a form of the CSPC effect when the context is defined by the location of an item.

To determine whether the N2 also modulates the ISPC, we examined ERP components in a Simon task in which two novel symbols are mostly spatially compatible with their respective key press, and two different novel symbols are mostly spatially incompatible with their respective key press. A larger N2 component for items associated with high conflict compared to items associated with low conflict (i.e., an N2 component modulated by the ISPC effect) would be consistent with the conflict-modulated Hebbian learning account of the ISPC effect (Blais et al., 2007; Verguts & Notebaert, 2008). A pure PEP account should see no such interaction for the ISPC on the N2 (Schmidt, 2013a,b; Schmidt & Besner, 2008). Therefore, both the PEP and the conflict-modulated Hebbian learning accounts predict a difference in the size of the N2 as a function of response conflict (i.e., the Simon effect, the difference between compatible and incompatible stimuli). However, only the conflict-modulated Hebbian learning accounts predict that the magnitude of the N2 should change as a function of ISPC context. To preview the results, we observe an N2 component modulated by the ISPC over Fz approximately 300 ms poststimulus.

## 2 | METHOD

### 2.1 | Participants

Twenty healthy volunteer college students were recruited from the introductory psychology participant pool at Arizona State University in exchange for course credit in accordance

with the Institutional Review Board. The experiment required approximately 30 min to complete, preceded by about 20 min for preparation of EEG recording.

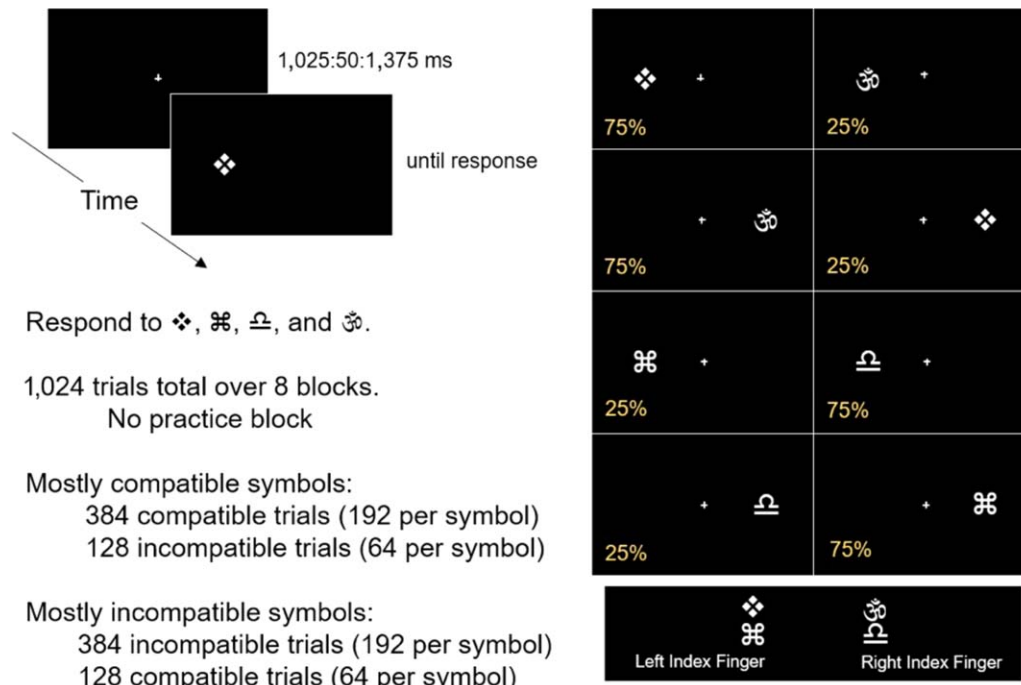
### 2.2 | Stimuli and procedure

Figure 1 shows a schematic of the experimental design. Subjects were seated approximately 90 cm from a 27" monitor running at  $2,560 \times 1,440$  pixels and presented with the symbols ❖ ❧ ⚡ ⚡ created by using the characters *v*, *z*, *d*, *\* in the Wingdings font, which appeared to the left or right of fixation. There were eight blocks of 128 trials each, totaling 1,024 trials. No practice blocks were presented. The intertrial interval was between 1,025 and 1,375 ms inclusive, in 50-ms increments, during which the fixation marker remained on the screen. The fixation marker disappeared during the presentation of the target symbol in each trial. In each block, half of the trials were compatible and the other half were incompatible. In the Simon task, compatibility is defined as whether the response mapping is spatially consistent with the location at which a stimulus appears. For every block, each symbol was either mostly compatible or mostly incompatible, such that a mostly compatible (incompatible) symbol was presented as compatible (incompatible) for 24 trials each block and presented as incompatible (compatible) for 8 trials each block. Whether a symbol was mostly compatible or mostly incompatible remained the same throughout the experiment. The presentation of stimuli was controlled using E-Prime, and responses were collected using the leftmost and rightmost keys on a standard PST response box.

### 2.3 | Equipment, recording, and preprocessing

EEG activity was recorded from 30 scalp locations, referenced to the linked mastoids, using silver/silver-chloride (Ag/AgCl) electrodes attached to an elastic cap (Neuromedical Supplies Inc.) and a Neuroscan SynAmps RT amplifier with Curry recording software. Horizontal eye movements and eye blinks were monitored with two pairs of bipolar electrodes positioned medially at the outer canthi and above and below the left eye, respectively. All impedances were kept below 5 k $\Omega$ . EEG activity was recorded at 1000 Hz and filtered from DC to 100 Hz. Continuous analog-to-digital conversion of the EEG and stimulus trigger codes were performed online by the Neuroscan acquisition interface system.

Offline data analyses were performed using EEGLAB (Delorme & Makeig, 2004). The continuous EEG data were downsampled to 250 Hz and filtered with a 1 to 30 Hz band-pass filter, using an infinite impulse response (IIR) Butterworth filter, and submitted to a GPU-optimized version of the infomax independent component analysis (ICA;



**FIGURE 1** Design schematic of experiment

Raimondo, Kamienkowski, Sigman, & Fernandez Slezak, 2012) procedure in EEGLAB. The ocular components in the ICA were identified using visual inspection (independently performed and then compared between two researchers) and then removed from the unfiltered raw data. The ICA procedure subsumed 1.1% of the data. The raw 1000 Hz data without ocular artifacts were then filtered to .1 to 30 Hz using an IIR Butterworth filter. The data were then epoched from -200 to 800 ms following the onset of the stimulus. A moving window 60 ms wide, moving in increments of 20 ms across the epoch (-200 to 800 ms), to detect peak-to-peak voltage differences exceeding 80  $\mu\text{V}$  across any channel was used to identify excess electrical noise. If four or fewer electrodes exceeded this threshold, those electrodes were removed and approximated using spherical interpolation. Otherwise, the trial was removed. This resulted in the exclusion of 1.0% (range: 0 to 10.2%) of correct trials across participants.

### 3 | RESULTS

#### 3.1 | Behavioral results

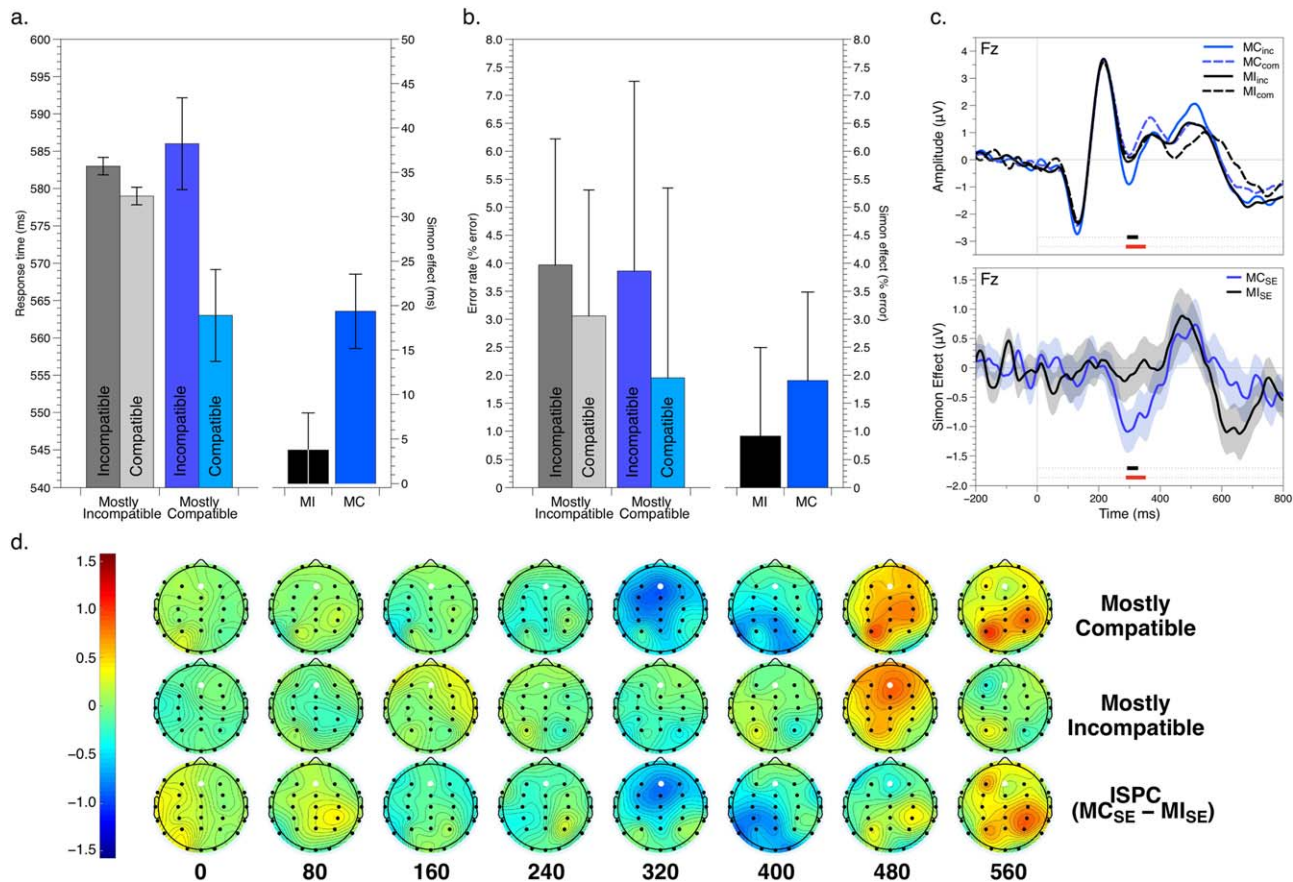
Incorrect trials and trials following an incorrect response were excluded from response time (RT) analysis (3.06%; ~6.1%, respectively). Following Hommel (1994), correct response times faster than 200 ms or slower than 1,000 ms were considered outliers and removed from the RT analysis (3.75%). The RT and % error data were then submitted to a 2 (Item Proportion Compatibility: mostly compatible vs. mostly incompatible)  $\times$  2 (Conflict: compatible vs. incom-

patible) repeated measures analysis of variance (ANOVA). There was a main effect of conflict,  $F_{RT}(1, 19) = 16.47$ ,  $p = .001$ ,  $\eta_p^2 = .464$ ;  $F_{\%E}(1, 19) = 14.27$ ,  $p = .001$ ,  $\eta_p^2 = .429$ , such that incompatible items (595 ms; 3.9% error) had slower response times and were less accurate than compatible items (579 ms; 2.2% error). Critically, in response times, there was an interaction between item proportion compatibility and compatibility,  $F_{RT}(1, 19) = 24.71$ ,  $p = .001$ ,  $\eta_p^2 = .565$ , such that the Simon effect for items that were mostly incompatible (583 vs. 579 ms,  $t(19) = 1.175$ ,  $p = .255$ ) was less than for items that were mostly compatible (586 vs. 567 ms,  $t(19) = 6.154$ ,  $p < .001$ ).

#### 3.2 | Electrophysiology

Examination of the scalp topography revealed that the N2 had maximal Fz (Figure 2d). Based on the temporal region of interest (ROI) from Blais et al. (2016), we focused on the 292- to 328-ms window to determine the extent to which this ISPC and the Blais et al. (2016) LSPC neural signals are related. The average ERP amplitudes of this ROI were submitted to the same Proportion  $\times$  Compatibility repeated measures ANOVA. There was a main effect of conflict,  $F(1, 19) = 4.41$ ,  $p = .049$ ,  $\eta_p^2 = .188$ , such that the incompatible items (-0.301  $\mu\text{V}$ ) were more negative than the compatible items (0.257  $\mu\text{V}$ ). Critically, there was an interaction between item proportion compatibility and compatibility,  $F(1, 19) = 6.92$ ,  $p = .016$ ,  $\eta_p^2 = .267$ , such that the Simon effect for items that were mostly incompatible (.045 vs. .155  $\mu\text{V}$ ,  $t(19) = .36$ ) was less than for items that were mostly





**FIGURE 2** (a) Left: Mean response time using ms for incompatible and compatible stimuli for each of the four Proportion × Compatibility conditions. Right: The Simon effect (incompatible – compatible) for each Proportion × Compatibility condition (MI = mostly incongruent, MC = mostly congruent). The difference in the Simon effect between the Proportion × Compatibility conditions (on right) is the item-specific proportion compatibility (ISPC) effect. Error bars indicate the root mean squared error. (b) Graph is organized the same as (a), but displays mean error rate (%) instead of ms. (c) ERP waveforms for the size of the Simon effect (SE) in the MC and MI conditions (top) and each of the four Proportion × Compatibility conditions (bottom). Shading indicates the standard error of the mean. The black horizontal line in each indicates the a priori temporal ROI (292 to 328 ms) from Blais et al. (2016), the red horizontal line in each indicates the significant time window ( $p < .05$ ) in the ERP waveform (281 to 358 ms), determined by random permutation tests described in the methods. (d) Difference wave scalp voltage potentials for the size of the SE (incompatible [inc] – compatible [com]) in the MC condition (top), the MI condition (middle), and the ISPC effect (bottom; MC effect – MI effect). The time point of these scalp distributions is indicated below each image and represents the instantaneous ranges between 0 and 560 ms poststimulus onset, in increments of 80 ms. The Fz electrode location is marked by a white electrode marker, all others are black

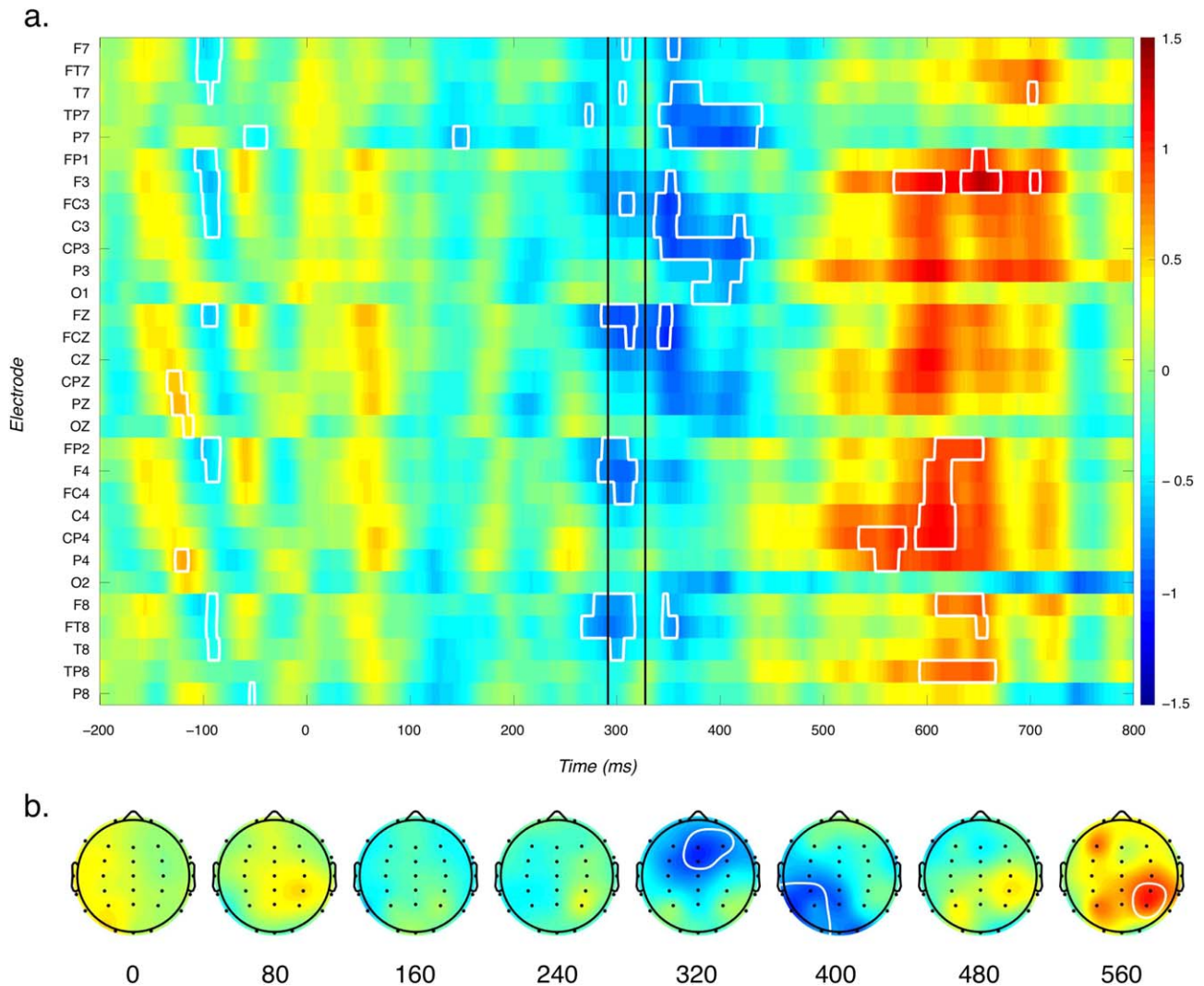
compatible (-.647 vs. .360  $\mu\text{V}$ ,  $t = 3.14$ ,  $p = .005$ ). The same analysis was done for electrodes FCz and Cz, and yielded a similar pattern of results.

In a separate analysis to determine a more precise time window for which the ISPC occurred in this task, and across which electrodes, randomization tests were conducted at each time point across the window from -200 to 800 ms across all electrodes. Specifically, a difference score for the mostly congruent (MC) and mostly incongruent (MI) conditions were created for each subject. Next, a distribution of ISPC scores was generated by randomly shuffling the order of subtraction for the MC and MI conditions over 10,000 simulations. If the observed ERP for the ISPC at a specific time point was below the 2.5th percentile or above the 97.5th percentile (i.e., alpha of .05, two-tailed) of the ERPs generated by pseudorandom subtraction, it was considered to be significant. This procedure determined that there

was a significant ISPC at Fz between 288 and 353 ms (see Figure 2c where vertical lines indicate the significant time window). Note that this randomization procedure led to nearly identical results to conducting a one-sample  $t$  test for the ISPC effect at every time point (281 to 358 ms).

#### 4 | DISCUSSION

The goal of this paper was to test whether the ISPC effect in a Simon task is independent from response conflict (Schmidt, 2013b) by examining the N2 component of the ERP, or whether it scales as a function of response conflict as it does for the CSPC effect (Blais et al., 2016). First, we found an ISPC effect in response times such that the difference between compatible and incompatible trials is greater for



**FIGURE 3** (a) Amplitude ( $\mu\text{V}$ ) of the ISPC effect from  $\pm 1.5 \mu\text{V}$ , where the y axis indicates the electrode location and the x axis time in ms. Areas outlined in white are determined to be significant ( $p < .05$ ) through permutation tests described in methods. Vertical black lines indicate the predetermined temporal ROI (from Blais et al., 2016). (b) Difference wave scalp voltage potentials ( $\mu\text{V}$ ) for the size of the ISPC effect, with the instantaneous time point for each scalp distribution indicated below. Outlined in white are the significant ( $p < .05$ ) clusters, determined by the permutation tests described in methods

mostly compatible trials (Figure 2a,b) than for mostly incompatible trials. This pattern was also present, but not statistically reliable, in the error data. Crucially, we found that the topography and latency of the N2 component at Fz (Figure 2c,d) is consistent with the results reported by Blais et al. (2016) with respect to the CSPC effect. That is, the negative deflection of the N2 component, observed in the ERP plot (Figure 2c), is greater for mostly compatible versus mostly incompatible trials, and we see the scalp distribution of this component maximally at frontal electrode sites (Figure 2d, Figure 3a,b). The significance of the N2 component is distributed across frontocentral electrode sites (Figure 3a,b) during our a priori temporal ROI from Blais et al. (2016), and consistent with previous literature (Folstein & Van Petten, 2008; Van Veen & Carter, 2002). This result adds to a growing body of evidence that, although simple associative learn-

ing is necessary to generate proportion congruency effects, it is not sufficient. For example, recent behavioral work shows that both response conflict and contingency learning interact (Whitehead et al., 2016) and task conflict and contingency learning interact (Levin & Tzelgov, 2016). We therefore argue that the conflict-modulated Hebbian learning account (Blais et al., 2007; Blais & Verguts, 2012; Verguts & Notebaert, 2008) provides a more complete account of these and other cognitive control phenomena.

Notably, these data further validate and build upon the conclusions of Shedden et al. (2013) who used ERP methods in a Stroop task to investigate the ISPC. They found a P1 component from medial occipital electrode sites that was modified by the ISPC, concluding that this early modulation of attention supported the online engagement of flexible cognitive control in the production of the ISPC. They did find a parietal N2

component sensitive to conflict; however, they did not find an N2 component modified by the ISPC, most likely due to conflict in the Stroop task being more closely associated with the N450 component (see Larson, Clayson, & Clawson, 2014).

In addition to our results showing concordance with conflict-modulated Hebbian learning models, based upon the framework of the conflict-monitoring hypothesis, our findings are also consistent with the framework proposed by Egner (2014). In this multiple levels of control framework, bottom-up stimulus-response associations and perceptual information are encoded into an event file (Hommel 1998), which includes top-down control states. Because the top-down control state is stored as part of the event file, one could argue that, when summed with the lower level information, it is effectively conflict-modulated Hebbian learning. Similarly, the dual-ISM account of the ISPC (Bugg, 2015) posits that bottom-up and top-down processes are on a continuum. The dual-ISM account is more explicit in that it specifies the conditions under which bottom-down versus top-down processing will dominate processing. Specifically the ISPC is primarily driven by bottom-up, contingency learning mechanisms when the irrelevant dimension captures attention, and the retrieval of top-down attentional settings when attention is captured by the relevant dimension. There should be no issues in incorporating these ideas into both the conflict-modulated Hebbian learning and the PEP models.

Despite not controlling for low-level confounds in this experiment, the presence of an N2 component indicating involvement of control processes in the production of the ISPC effect are difficult to explain within the PEP framework. We speculate that modifying the PEP account to allow it to adjust attentional focus in high conflict states, even at a rudimentary level such that attention focus operates as a light-switch—either *on* in difficult situations or *off* in easy situations—could account for these results. This change would allow the PEP model to explain these and other findings (see Blais et al., 2016; Whitehead et al., 2016). However, the additions of this mechanism would effectively transform it to a conflict-modulated Hebbian learning account. This is not to deny the possibility that the frontal N2 component modulated by the ISPC effect could be involved in a wide range of other cognitive processes and mechanisms besides conflict. Although these results are inconsistent with the PEP, future work examining more basic features of the N2 component in relation to stimulus-response learning in cognitive control tasks should be conducted to gain a better understanding of the underappreciated role of this facet of these tasks.

## 4.1 | Conclusions

It is clear that stimulus-response learning processes are necessary to generate an ISPC effect; what is unclear is whether

they are sufficient. This debate led us to compare two computational models of the ISPC that are conceptually different, but mathematically quite similar in many regards. Where they do differ is on the issue of whether response conflict impacts stimulus-response learning. This is the fundamental tenet behind the conflict-modulated Hebbian learning account (i.e., Blais et al., 2007; Blais & Verguts, 2012; Verguts & Notebaert, 2008). Conversely, the PEP model (Schmidt, 2013b) argues quite strongly that they are independent. The current results show that an ERP component associated with response conflict, the N2 component, is modulated by the ISPC. This finding adds to a growing body of literature (Blais et al., 2016; Whitehead et al., 2016) showing that, in situations requiring selective attention, the norm appears to be that stimulus response learning and response conflict interact to produce optimal behavior.

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