

Item-Specific Proportion Congruency Uncovers Different Forms of Attentional Control: An event-related fNIRS Study

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ABSTRACT

Introduction: Recent research has shown that attentional control can be modulated at the item-specific level, meaning that different control strategies can be applied to individual stimuli based on their relative frequencies within a given set. However, an alternative account suggests these findings may be confounded by stimulus-response contingency learning. Contingency is the proportion of trials where a distractor appears with its corresponding target; higher contingency enables faster associative response preparation, producing behavioral effects that mimic item-specific control. While neuroimaging studies provide some evidence for anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) involvement during controlled processes, differentiating item-specific control from contingency learning at the neural level remains challenging. In particular, no prior study has examined how temporal factors influence prefrontal engagement during these two processes.

Methods: This study utilized item-specific proportion congruency (ISPC) manipulation via the flanker task. Hemodynamic activity in the prefrontal cortex was measured using functional near-infrared spectroscopy (fNIRS) alongside reaction time and error rates. The role of contingency learning was examined by manipulating stimulus onset asynchrony (SOA). A 2 (congruency) × 2 (proportion congruency) × 3 (SOA: -250, 0, +250 ms) within-subject design with repeated-measures ANOVA was used. To

control for multiple comparisons across the 16 channels and 7 ANOVA effects, a hierarchical false discovery rate (FDR) procedure was applied.

Results: The ISPC effect was significant and modulated by SOA, being significant at -250 and 0 ms but not at +250 ms. In fNIRS data, the SOA main effect was significant in eight channels (3,9–14,16), and the ISPC effect was significant in four channels (1, 10, 11, and 12), after hierarchical FDR correction. The three-way interaction was not significant in any channel. Contingency analysis revealed a main effect, with the largest contingency effect at -250 ms. The fNIRS contingency main effect was also significant in channels 1, 10, 11, and 12.

Conclusion: While behavioral results mostly support contingency learning, fNIRS data revealed ISPC-related activation in prefrontal channels with sensitivity to BA 46 (lateral, channel 1) and the BA 10/BA 11 overlap zone (medial, channels 10–12), with channel 11 emerging as a convergence point for both SOA and ISPC effects. This spatial dissociation is consistent with the possible involvement of both control and learning processes operating in parallel within distinct prefrontal subregions.

Keywords: Attention, dorsolateral prefrontal cortex, hemodynamics, learning, orbitofrontal cortex, spectroscopy

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INTRODUCTION

Cognitive control is the ability to flexibly adjust information processing to align with current task goals, particularly when automatic processes conflict with task demands. It involves the capacity to regulate information and make adaptive adjustments during cognition. This phenomenon has been extensively investigated using the flanker task (1). In this task, participants identify a central target letter within a sequence of letters that serve as distractors. Responses are faster and more accurate when the distractors are identical to the target (congruent condition, e.g., FFF) than when they are not (incongruent condition, e.g., DFD). The congruency effect, computed as the difference between incongruent and

Highlights

- Behavioral results mostly support the contingency learning mechanism.
- fNIRS data support both item-specific control and contingency learning accounts.
- Contingency learning and control mechanisms can operate together.

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congruent conditions, serves as a measure for control, estimating the relative influence of the target and distractor on response selection.

A pioneering study showed cognitive control could be modulated in an item-specific manner (2). In the related experiment, half of the items were presented mostly congruent ([MC], 75% congruent, 25% incongruent), while the other half was presented mostly incongruent ([MI], 75% incongruent, 25% congruent), and intermixed randomly. The congruency effect was larger for the MC items and smaller for the MI items. The difference between them is called the *item-specific proportion congruency* (ISPC) effect, reflecting an item-specific form of control that is triggered by the stimulus itself. Attentional control is differentially modulated for MC and MI items, in a lax or strict way, respectively, in a bottom-up manner. Critically, unlike the list-level proportion congruency effect, traditionally attributed to top-down strategic biasing of attention across an experimental list (3), the ISPC manipulation holds the overall list-level congruency constant (%50) in the same experimental session. Therefore, any change of the congruency effect cannot be attributed to a global shift in control and must be related to properties of individual items. In this sense, the ISPC manipulation introduced a new form of control, item-specific, expanding the existing control accounts.

As an alternative perspective, Schmidt and Besner (2008) proposed that the stimulus-response contingency learning mechanism can account for the ISPC effect, rather than item-specific control (4). For each distractor, contingency is calculated as the proportion of trials where that distractor appears with its corresponding target. There is a high contingency in congruent items in the MC set, and incongruent items in the MI set in the ISPC experiments (e.g., $16/(16+4) = 0.80$, see Table 1). On the other hand, the incongruent items in the MC set, and the congruent items in the MI set have low contingency (e.g., $4/(16+4) = 0.20$). When contingency is high, participants could predict the response based on the contingency between the distractor and response without utilizing cognitive control. This creates associative learning, facilitating anticipatory response preparation, resulting in faster responses in high contingency items. These fast responses can produce a learning-based ISPC effect without the engagement of item-specific control. By reanalyzing the original data of Jacoby et al. (2003, 2), Schmidt and Besner (2008) show that high contingency items are responded to faster than low contingency items (4). Furthermore, there is no interaction between contingency and congruency; the congruency effect is identical across high- and low-contingency items. Actually, the item-specific control account predicts an interaction between them. Heightened control states for incongruent items in the MI set should reduce the congruency effect in high-contingency incongruent items, which in turn creates an interaction effect, but this was not the case in the reanalysis. For this reason, Schmidt and Besner (2008, 4) claimed that the ISPC effect is a combination of two distinct processes – the congruency effect and contingency learning – rather than being

a manifestation of item-specific control of attention. However, the underlying mechanism of the ISPC effect remains a topic of ongoing debate in behavioral studies, particularly concerning the contribution of item-specific control and contingency learning. One line of research supports the dominance of contingency learning, whereas another highlights the contribution of both mechanisms depending on the task design (5–12).

Neuroimaging studies would also help disentangle the relative contributions of contingency learning and item-specific control to the ISPC effect. Blais and Bunge (2010) conducted a functional magnetic resonance imaging (fMRI) study and showed that ACC and dLPFC activations correspond with the proportion congruency (PC) of individual items, supporting item-specific control (13). In a second fMRI study, Grandjean et al. (2013) employed the same ISPC design (14) as the one used by Jacoby et al. (2003,2). The congruency effect in the MC set was significant, demonstrating an activation difference between congruent and incongruent items in the ACC and the dLPFC regions. Nonetheless, in the MI set, there were no significant activation differences observed in either the ACC or dLPFC. Grandjean et al. (2013,14) also conducted a contingency analysis on their data (14), similar to Schmidt and Besner (2008,4). The ACC and dLPFC activity did not show the congruency and contingency interaction: the activation difference between congruent and incongruent items within the ACC-dLPFC network was similar across high- and low-contingency items, supporting contingency learning. Taken together, these neuroimaging findings provide mixed evidence regarding the involvement of the ACC-dLPFC network in relation to item-specific control.

Despite investigations at both behavioral and neural levels, it remains unclear whether the ISPC effect primarily reflects item-specific control or contingency learning at the neural level. Notably, prior neuroimaging studies have focused on classic task designs and have not examined how temporal factors may influence prefrontal engagement during the differential engagement of contingency learning and item-specific control. To address this limitation, the current study employed a manipulation of Stimulus Onset Asynchrony (SOA), that is, the temporal interval between distractor and target onset, while measuring prefrontal activity using functional near-infrared spectroscopy (fNIRS). Manipulating SOA is theoretically informative because temporal separation between distractor and target may differentially affect the use of contingency learning and item-specific control mechanisms. Specifically, varying SOA enables examination of the temporal dynamics of the ISPC effect at the neural level, given behavioral evidence showing that the ISPC effect disappears when the distractor dimension is presented +200 ms after the target (11). This pattern suggests a limited temporal window during which the distractor can either serve as a predictive cue leading to contingency learning or trigger item-specific reactive control before response initiation.

In the present study, we therefore investigated prefrontal cortex involvement in the ISPC effect using fNIRS, a non-invasive optical neuroimaging technology that measures the hemodynamic response in the human cortex using light emitters and detectors placed on the scalp (15–17). This method enables calculating the relative concentrations of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) based on absorption changes in the near-infrared spectrum (18–20). Although fNIRS is not suitable for observing deep brain tissues (21,22), it remains a reliable technique for measuring hemodynamic responses in cortical regions near the scalp, such as the prefrontal cortex (23). Its cost-effectiveness allows for larger sample sizes, enhancing statistical power.

Table 1. Stimulus organization in a block

Target flanker	D	F	J	K
D	16	4		
F	4	16		
J			4	16
K			16	4

The stimulus organization was identical for all three blocks of SOA. For each participant, letters were randomly assigned to the mostly congruent and mostly incongruent conditions.

Crucially, no prior neuroimaging study has combined SOA manipulation with direct measurement of prefrontal activity to dissociate control-based and learning-based accounts of the ISPC effect. Manipulating the temporal asynchrony between distractor and target onset (stimulus onset asynchrony [SOA]) is theoretically informative because it can differentially affect the contributions of contingency learning and item-specific control (11). Accordingly, we examined whether hemodynamic activity within the prefrontal cortex reflects the mechanisms underlying the ISPC effect and their modulation by SOA. We formulated two predictions. First, if item-specific control drives the ISPC effect, activity in channels with BA 46 sensitivity (associated with dlPFC in prior fMRI literature; see 13, also see 24) should show the ISPC effect, and this effect should be modulated by SOA in a pattern paralleling the behavioral data. Second, if contingency learning contributes to the ISPC effect, activation in anterior prefrontal channels with sensitivity to learning-related areas (e.g., BA 11), to the extent accessible by fNIRS, should also show the ISPC effect, potentially with SOA-dependent modulation reflecting the temporal window available for associative learning. If both mechanisms contribute, we would expect ISPC-related activation in channels sensitive to both BA 46 and BA 11, though the pattern of SOA modulation may help clarify their relative contributions.

METHODS

Behavioral replication of this experiment was reported in the supplementary material. Gemini 3 Flash and Grammarly Desktop were used to correct grammatical errors and enhance academic writing style.

Participants

Sixty-one undergraduate students from Izmir University of Economics participated in the experiment. All participants reported having normal or corrected-to-normal vision, not using any psychoactive drugs, not having reading problems, not having attention deficit disorder, and being native Turkish speakers. Before the experiment, all participants read a brief description of the study and approved an online informed consent form. During the analysis, 17 participants were excluded from the analysis due to physiological and/or non-physiological noise sources for the fNIRS signal values. Data from one participant was removed from the analysis since they made errors more than three standard deviations from the mean percentage of errors, suggesting task misunderstanding or disengagement. All analyses were conducted with the remaining 40 (30 females, 10 males, $M_{age} = 21.28$) participants.

Ethics

The study was conducted in accordance with the Declaration of Helsinki, and the procedure was approved by the Ethics Committee of the Izmir University of Economics (B. 30.2. IEÜ. 0.05.05–020–052; date: 07.04.2017). All participants gave written consent for participation at the beginning of the experiment.

Design and Statistics

2 (congruency: congruent, incongruent) $\times$ 2 (PC: MC, MI) $\times$ 3 (SOA: -250 ms, 0 ms, +250 ms) repeated measures ANOVA was used in the study for reaction times (RTs) and PE. The behavioral data were cleaned in R (R Core Team, Vienna, Austria), and fNIRS data were processed in fNIRSOFT-PRO (BIOPAC, California, USA) (25). Both behavioral and fNIRS data were analyzed in JASP (JASP Team, Amsterdam, The Netherlands). All ANOVAs were pure within-subjects designs with no between-subjects factors or covariates.

To evaluate the data against the predictions of both competing theoretical accounts, the 2 $\times$ 2 (PC $\times$ Congruency) subdesign was interpreted under two theoretically motivated parameterizations. Under the *proportion congruency framing*, which aligns with the item-specific control account

(2,7), the critical test is the PC $\times$ Congruency interaction – the ISPC effect itself. Under the *contingency framing*, which aligns with the contingency learning account (4), the critical test is the Contingency main effect: faster responses to high- versus low-contingency items, where high-contingency cells correspond to {MC-congruent, MI-incongruent} and low-contingency cells correspond to {MC-incongruent, MI-congruent}. These two parameterizations are orthogonal rotations of the same model and yield identical test statistics on identical data; they are not independent analyses but alternative encodings that make each account's theoretically central contrast visible as a main effect rather than as a component of a higher-order interaction. Specifically, the Contingency main effect is algebraically equivalent to the PC $\times$ Congruency interaction, and the Contingency $\times$ Congruency interaction is algebraically equivalent to the PC main effect, with the Congruency main effect invariant across framings. Accordingly, all effects are reported under the PC framing for statistical correction purposes, with the contingency framing used to highlight the critical discriminating test: the Contingency $\times$ Congruency interaction (equivalent to the PC main effect under the alternative framing). A significant Contingency $\times$ Congruency interaction would support the control account; its absence would support the learning account (4).

Instruments (and Procedure)

The stimuli consisted of three letters presented in a row, with the target letter in the center and the same two letters on the left and right sides. In congruent trials, the target and flanker letters were identical (e.g., DDD). In incongruent trials, they were different (e.g., FDF). All stimuli were presented at the center of the screen, using a 30-point black Courier New font against a white background. The four letters (D, F, J, and K) were divided into two sets, with one set serving as the MC set and the other as the MI set (Table 1). These sets were randomly intermixed, as in previous studies (2), enabling the observation of item-specific effects rather than list-wide effects. The assignment of letters to the MC and MI sets was also randomized for each participant. Additionally, we manipulated the SOA between the target and the flanker letters.

In the flanker-first condition (SOA = -250 ms), the flanker letters were presented for 250 ms before the target was shown in between them. For the simultaneous-presentation condition (SOA = 0 ms), the flanker and target letters were shown simultaneously. Conversely, in the target-first condition (SOA = +250 ms), the target letter was presented for 250 ms before flanker letters were introduced (see Figure 1). The stimuli remained visible on the screen until a response was recorded or the 1500 ms time limit was reached, trials exceeding this duration were coded as 'no response'. The SOA remained constant within each block of 80 trials. We specifically preferred the blocked SOA procedure since random variation of the SOA trial-to-trial would introduce temporal uncertainty. This may encourage participants to use cautious "wait-and-see" strategies that could obscure the mechanisms under investigation. In contrast, blocking SOA allows participants to develop stable temporal expectations within each block, thereby providing a clearer assessment regarding the effect of SOA. Although different SOA blocks may create distinct cognitive sets, this was a theoretically motivated aspect of the design. Specifically, the study aimed to examine whether different temporal dynamics systematically modulate the ISPC effect and its underlying mechanisms.

Each SOA condition included 80 trials (240 trials in total), providing sufficient exposure for both control adjustments and contingency learning processes. Prior evidence indicates that the ISPC effect reliably emerges even within the first 16 trials (2), suggesting that the present design provides sufficient conditions for the effect to emerge within each block. Furthermore, previous research has shown that blocked SOA procedures can produce reliable ISPC effects (11). Stimulus

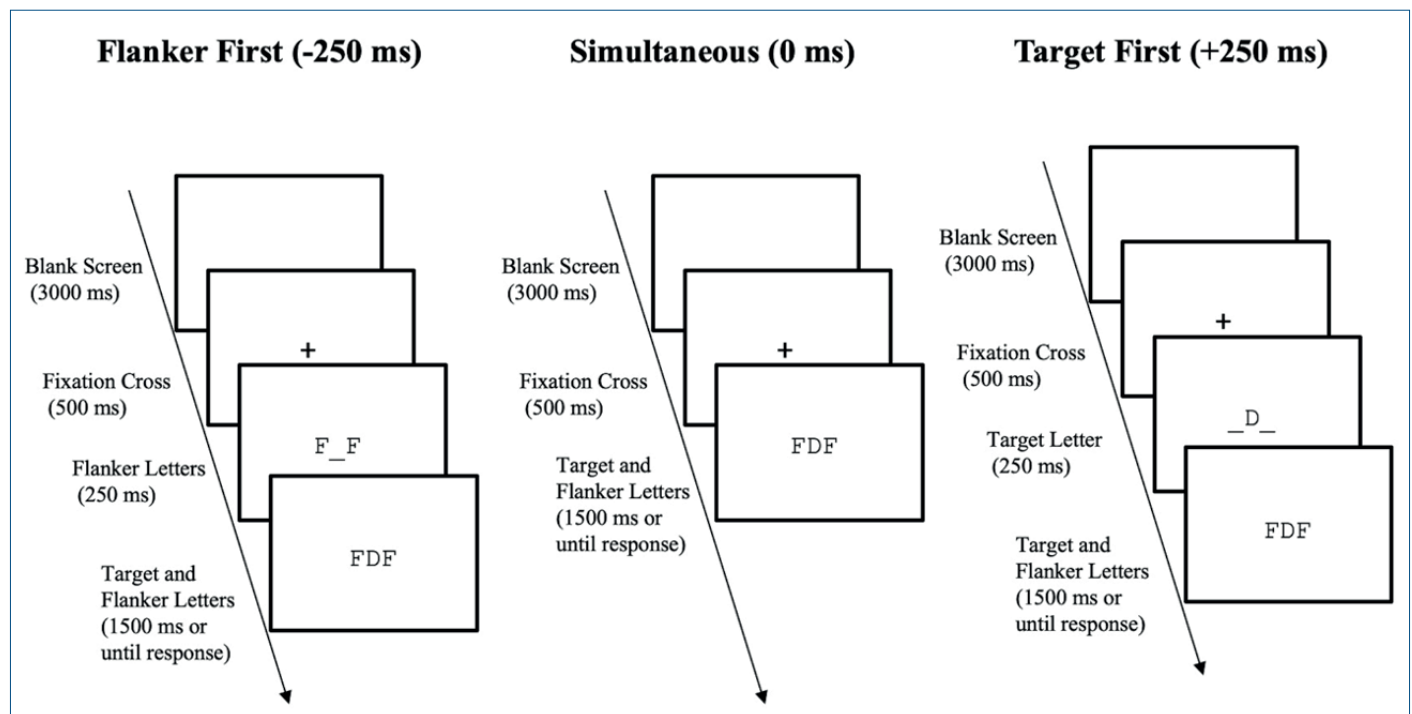


Figure 1. Sample stimulus presentation fNIRS Procedure

presentation and data collection were controlled using E-Prime® software with the Serial Response Box® (Psychology Software Tools, Pittsburgh, USA). Participants were given oral and written instructions to respond to the target letter by pressing the corresponding key as quickly and as accurately as possible while ignoring the flanker letters. Each trial was initiated by a blank screen lasting 3000 ms, followed by a fixation symbol displayed for 500 ms, and subsequently, the appearance of the target and/or flanker letters, depending on the SOA condition. The experimental session consisted of 240 trials (one block of 80 trials for each SOA condition). The order of the SOA blocks was randomized for each participant.

Hemodynamic activity of the prefrontal cortex was observed by fNIR 200A stand-alone 16-channel functional brain imaging system (fNIR Devices, LLC [Potomac, MD, USA]), and COBI Studio (BIOPAC, California, USA) was used to collect data from the fNIR Imager. Before the experiment was started, the participant's forehead was cleaned to remove dirt, sudation, and cosmetic materials. Then the fNIR sensor pad was placed on the forehead of the participants (see Figure 2). Finally, before the recording, the signal values were checked for each participant. If the signal values were not between 400 mV and 4000 mV, the device was stopped, and the light intensity and detector gain values were adjusted until appropriate signal values were observed. After the device settings arrangement, hemodynamic activity was recorded. Stimulus presentation was programmed with E-prime 2.0.

fNIRS Data Pre-Processing

The data was prepared for analysis by using fNIRSOFT-PRO (BIOPAC, California, USA) analysis software (25). Each participant's raw data was assessed in terms of the quality of signal values. Participants whose signal intensity fell outside the acceptable range (400–4000 mV) due to hair beneath the sensor, or who showed unstable optical coupling due to excessive sweating, were identified as non-physiological noise sources. Additionally, the SMAR (sliding windows motion artifact rejection) algorithm was applied to refine outliers and abrupt spikes caused by head motion during the experiment (29). The number of participants excluded

is reported in the Participants section. Our exclusion rate is relatively high, possibly due to strict quality criteria, participant hair characteristics (dense dark hair), and the relatively long duration of the experiment, which may have introduced motion artifacts. Future studies should use newer fNIRS systems with improved optodes and more frequent breaks.

Breathing rate, changes in heartbeat, and blood pressure (Mayer cycles) also affect blood circulation (30), which causes high-frequency noise in raw fNIRS signals. To remove these local changes from the data, a linear-phase finite impulse response (FIR) filter with order 20 and cut-off frequency 0.1 Hz was applied after the SMAR application (29,31). Finally, fNIRS markers were converted to hemodynamic responses by the modified Beer-Lambert Law. The change in blood oxygenation and blood volume amounts during each congruency block was calculated, and the data were then ready to be analyzed and visualized on topography.

Hemodynamic responses were extracted at the trial level, and average hemodynamic activity was calculated for each condition and each participant. A channel-wise statistical analysis was conducted based on this data. Specifically, a repeated-measures ANOVA with the same $2 \times 2 \times 3$ factorial design used for the behavioral data was performed separately for each of the 16 channels. Greenhouse-Geisser correction was applied for violations of the sphericity assumption. To control for multiple comparisons across both the 16 channels and the 7 ANOVA effects, we applied a hierarchical false discovery rate (FDR) procedure (32,33). In the first stage, the 16 channel-level p-values within each of the 7 effects were combined into a single effect-level p-value using Simes' combined test (34), and the 7 combined p-values were submitted to Benjamini-Hochberg FDR correction at $q = 0.05$ to determine which effects showed evidence of any non-null channel across the cortex. In the second stage, channel-level Benjamini-Hochberg FDR ($q = 0.05$) was applied across the 16 channels within each of the effects that passed the first stage; effects failing the first stage were not tested at the channel level. This two-stage procedure formally controls FDR across the full channel-by-effect grid while preserving statistical power for effects with spatially coherent signal (33). FDR was preferred over the Bonferroni correction because

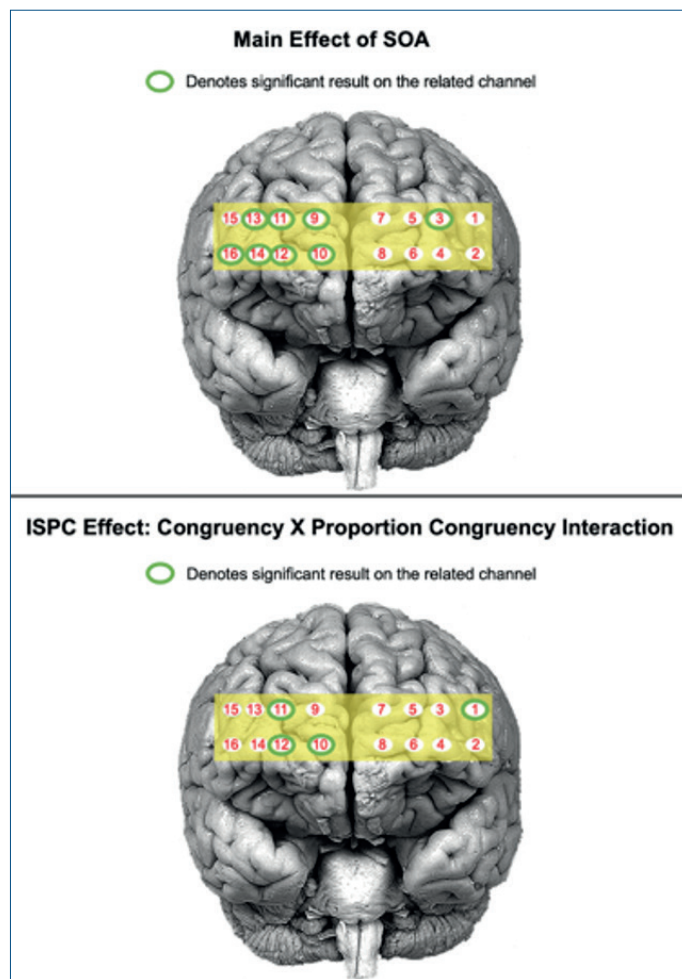


Figure 2. Lateral channels (left 1, 2; right 15, 16; BA 46/10), medial channels (left 5, 6; right 11, 12; BA 10/11), frontopolar channels (left 7, 8; right 9, 10; BA 10). Channels 3, 4 (left) and 13, 14 (right) span multiple areas (BA 10, 11, 46, 47). Channel-to-Brodmann area correspondence is based on the standardized montage (26,27) and the manufacturer's mapping (BIOPAC; cf. 28) and should be considered approximate.

the latter assumes test independence, whereas adjacent fNIRS channels share hemodynamic signal due to the spatial spread of the prefrontal hemodynamic response and shared physiological noise sources – conditions under which Bonferroni becomes overly conservative and underpowered (35). Notably, we did not employ a general linear model (GLM) approach or region-of-interest (ROI) averaging; instead, each channel was treated as a separate dependent variable, yet preserving a strict significance criterion by FDR correction. This channel-wise approach was chosen to preserve the spatial specificity of the fNIRS montage and to avoid assumptions about functional homogeneity within predefined cortical regions.

RESULTS

Behavioral Results

Trials without responses, trials with incorrect responses, trials following a no-response or an incorrect response, and trials with RTs smaller than 150 ms were excluded from the RT analysis. The 150 ms threshold is standard in flanker control literature, reflecting premature responses (minimum time for perception and +response preparation). It is known that non-recursive outlier elimination procedures are sensitive to sample size and the skewness of the population. For this reason, we adopted a more dynamic and valid approach that is a recursive outlier

elimination (36). In this procedure, for each participant and each condition, the mean and SD were calculated separately, and outliers were removed according to criteria that are bound to sample size dynamically. The procedure was repeated until no outliers remained (also see reference 5 for a similar implementation). After this elimination, the RT analysis was conducted using the remaining 96% of the trials. For the PE analysis, only trials with no response were excluded from the analysis. Greenhouse-Geisser correction was applied for the violations of the sphericity assumption.

Proportion Congruency (PC) Analysis

The average RT and PE for the conditions are presented in Table 2. For the RT data, the main effect of congruency was significant, $F(1,39) = 56.21$, $MSE = 2626.32$, $p < 0.001$, $\eta_p^2 = 0.59$. Responses were faster in congruent trials ($M = 662$) than in incongruent trials ($M = 697$). There was a significant main effect of SOA, $F(1.77, 69.18) = 34.56$, $MSE = 7652.86$, $p < 0.001$, $\eta_p^2 = 0.47$. Responses were fastest in the flanker-first trials ($M = 639$), followed by the target-first trials ($M = 683$) and simultaneous-presentation trials ($M = 716$). The main effect of PC was not significant, $F(1,39) = 0.95$, $MSE = 22,579.89$, $p = 0.34$, $\eta_p^2 = 0.02$. The two-way interaction between congruency and SOA was significant, $F(1.88, 73.45) = 6.70$, $MSE = 4375.15$, $p = 0.003$, $\eta_p^2 = 0.15$. The largest congruency effect was observed for the flanker-first condition ($M = 59$), followed by the simultaneous-presentation condition ($M = 40$) and target-first condition ($M = 7$). The two-way interaction between congruency and PC, namely the ISPC effect, was significant, $F(1,39) = 12.59$, $MSE = 2916.75$, $p = 0.001$, $\eta_p^2 = 0.24$, which indicates that the congruency effect was smaller for the MI set ($M = 18$) than for the MC set ($M = 53$). The two-way interaction between SOA and PC, was significant, $F(1.96, 76.62) = 3.22$, $MSE = 3191.08$, $p = 0.046$, $\eta_p^2 = 0.08$. The three-way interaction among congruency, SOA, and PC was significant, $F(1.90, 74.07) = 3.73$, $MSE = 2923.71$, $p = 0.03$, $\eta_p^2 = 0.09$.

Separate 2 (congruency: congruent, incongruent) $\times$ 2 (PC: MC, MI) repeated measures ANOVAs were conducted for each of the SOA conditions. The two-way interaction between congruency and PC, namely the ISPC effect, was significant for the flanker-first condition (68 ms), $F(1,39) = 12.47$, $MSE = 3715.39$, $p = 0.001$, $\eta_p^2 = 0.24$, and simultaneous-presentation condition (33 ms), $F(1,39) = 5.02$, $MSE = 2177.83$, $p = 0.03$, $\eta_p^2 = 0.11$. However, it was not significant for the target-first condition (4 ms), $F(1,39) = 0.06$, $MSE = 2576.04$, $p = 0.81$, $\eta_p^2 = 0.001$ (see Figure 2). None of the main effects or interactions were significant for the PE's ($p > 0.05$).

Contingency Analysis

As described in the Method section, the contingency framing is an algebraically equivalent re-parameterization of the 2 $\times$ 2 (PC $\times$ Congruency) subdesign: the Contingency main effect corresponds to the PC $\times$ Congruency interaction, and the Contingency $\times$ Congruency interaction corresponds to the PC main effect. The statistics reported below are therefore identical to those reported in the PC analysis above; they are presented under the contingency framing to facilitate interpretation under the learning account (4).

For the RT data, the main effect of contingency was significant, $F(1,39) = 12.59$, $MSE = 2916.75$, $p = 0.001$, $\eta_p^2 = 0.24$ (equivalent to the PC $\times$ Congruency interaction reported above). Responses were faster in high contingency trials ($M = 671$) than in low contingency trials ($M = 688$). The two-way interaction between contingency and SOA was significant, $F(1.90, 74.07) = 3.73$, $MSE = 2923.71$, $p = 0.03$, $\eta_p^2 = 0.09$ (equivalent to the SOA $\times$ PC $\times$ Congruency three-way interaction). The largest contingency effect (low contingency minus high contingency) was observed for the flanker-first condition ($M = 34$ ms difference between high and low contingency conditions), followed by the simultaneous-presentation condition ($M = 17$) and target-first condition ($M = 2$). Critically, the two-way

Table 2. Mean reaction times (RT) and percentage of errors (PE) for each condition

Proportion congruent	Congruency	Stimulus onset asynchrony					
		Flanker first		Simultaneous		Target first	
		RT	PE	RT	PE	RT	PE
Mostly congruent	Congruent	577 (17)	3.6 (0.9)	687 (16)	4.0 (0.6)	674 (13)	4.8 (0.9)
	Incongruent	670 (15)	3.5 (0.9)	744 (19)	7.5 (1.5)	683 (18)	4.4 (1.1)
Mostly incongruent	Congruent	642 (22)	3.1 (1.1)	704 (21)	3.1 (1.1)	685 (18)	5 (1.2)
	Incongruent	667 (14)	4.3 (0.7)	727 (17)	4.3 (0.7)	690 (18)	4.9 (0.8)
ISPC Effect		68	-1.3	33	2.3	4	-0.3

Standard errors are given in parentheses; reaction times are in milliseconds depicted in parentheses.

interaction between congruency and contingency was not significant, $F(1,39)=0.95$, $MSE=22.579.89$, $p=0.34$, $\eta^2_p=0.02$ (equivalent to the PC main effect). This interaction is the test that discriminates between the two theoretical accounts: the item-specific control account predicts its presence, whereas the contingency learning account predicts its absence (4). The three-way interaction among congruency, SOA, and contingency was significant, $F(1.96, 76.62)=3.22$, $MSE=3191.08$, $p=0.046$, $\eta^2_p=0.08$ (equivalent to the SOA $\times$ PC interaction).

Separate 2 (congruency: congruent, incongruent) $\times$ 2 (contingency: high, low) repeated measures ANOVAs were conducted for each of the SOA conditions. The main effect of contingency was significant in the flanker-first, $F(1,39)=12.47$, $MSE=3715.39$, $p=0.001$, $\eta^2_p=0.24$, and the simultaneous-presentation conditions, $F(1,39)=5.02$, $MSE=2177.83$, $p=0.03$, $\eta^2_p=0.11$, but not in the target-first condition, $F(1,39)=0.06$, $MSE=2576.04$, $p=0.81$, $\eta^2_p=0.001$. The two-way interaction between congruency and contingency was significant for the flanker-first condition, in wrong direction (see 7), (see Figure 4), $F(1,39)=4.46$, $MSE=8551.43$, $p=0.04$, $\eta^2_p=0.10$, but was not significant for the simultaneous-presentation and the target-first conditions ($p>0.05$). None of the main effects or interactions were significant for the PE's ($p>0.05$).

fNIRS Results

Proportion Congruency (PC) Analysis

Oxy-Hb measures from sixteen channels were separately submitted to 2 (congruency: congruent, incongruent) $\times$ 2 (PC: MC, MI) $\times$ 3 (SOA: -250 ms, 0 ms, +250 ms) repeated measures ANOVAs (Note: For some of the participants data from certain channels could not be used due to noise, and analyses were conducted without these channels. For this reason, df values may differ along the fNIRS results). Greenhouse-Geisser correction was applied for violations of the sphericity assumption. Multiple comparisons across the 16 channels and 7 ANOVA effects were controlled using the hierarchical FDR procedure described in the Methods section.

Stage 1: Effect-level screening. The Simes-combined p-values across the 16 channels, submitted to Benjamini–Hochberg FDR at $q=0.05$, indicated that only two effects contained evidence of any non-null channel across the cortex: the SOA main effect ($p_{\text{Simes}}=0.008$, $p_{\text{FDR}}=0.028$) and the PC $\times$ Congruency interaction ($p_{\text{Simes}}=0.005$, $p_{\text{FDR}}=0.028$). The remaining effects – including the PC main effect (i. e., the Contingency $\times$ Congruency interaction under the contingency framing; $p_{\text{Simes}}=0.120$, $p_{\text{FDR}}=0.280$), the Congruency main effect ($p_{\text{FDR}}=0.912$), and all remaining two- and three-way interactions (all $p_{\text{FDR}}\geq0.912$) – did not pass Stage 1 and were therefore not tested at the channel level.

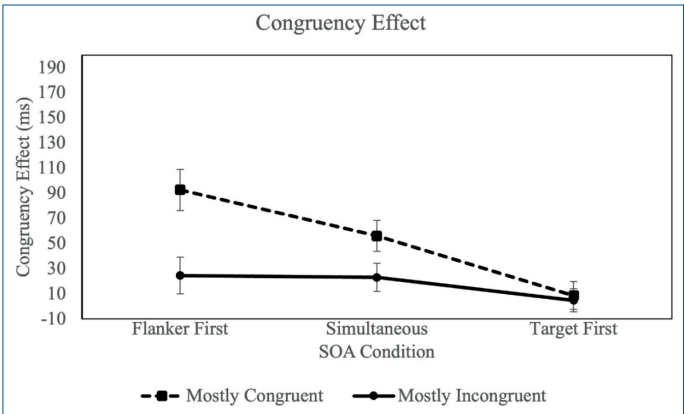


Figure 3. Mean congruency effects as a function of proportion congruency and stimulus onset asynchrony (error bars: standard errors; ms: millisecond).

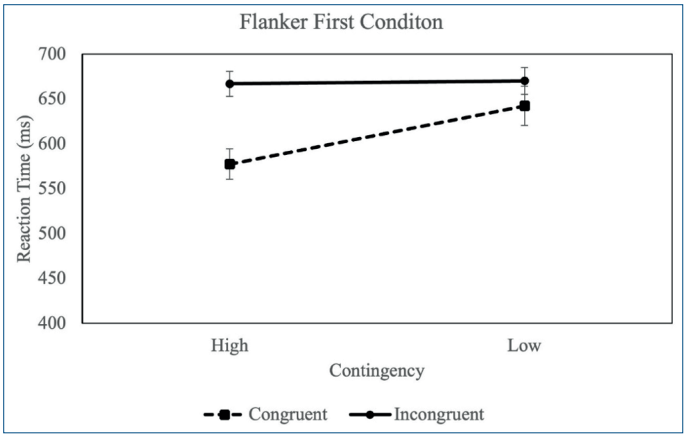


Figure 4. Mean congruency effects as a function of contingency in the flanker first condition (error bars: standard errors; ms: millisecond).

Stage 2: Channel-level tests for surviving effects. The main effect of SOA was significant in eight channels: channel 3 ($F(2,78)=4.59$, $p_{\text{FDR}}=0.037$, $\eta^2_p=0.105$), channel 9 ($F(1.97, 76.71)=4.16$, $p_{\text{FDR}}=0.040$, $\eta^2_p=0.106$), channel 10 ($F(1.85, 71.96)=4.51$, $p_{\text{FDR}}=0.037$, $\eta^2_p=0.104$), channel 11 ($F(1.78, 69.49)=8.40$, $p_{\text{FDR}}=0.008$, $\eta^2_p=0.177$), channel 12 ($F(1.92, 74.83)=4.51$, $p_{\text{FDR}}=0.037$, $\eta^2_p=0.104$), channel 13 ($F(1.94, 75.55)=5.65$, $p_{\text{FDR}}=0.027$, $\eta^2_p=0.126$), channel 14 ($F(1.98, 77.13)=4.33$, $p_{\text{FDR}}=0.039$, $\eta^2_p=0.100$), and channel 16 ($F(1.97, 73.03)=8.14$, $p_{\text{FDR}}=0.008$, $\eta^2_p=0.180$). The SOA main effect was not significant in the remaining channels (see Figure 5).

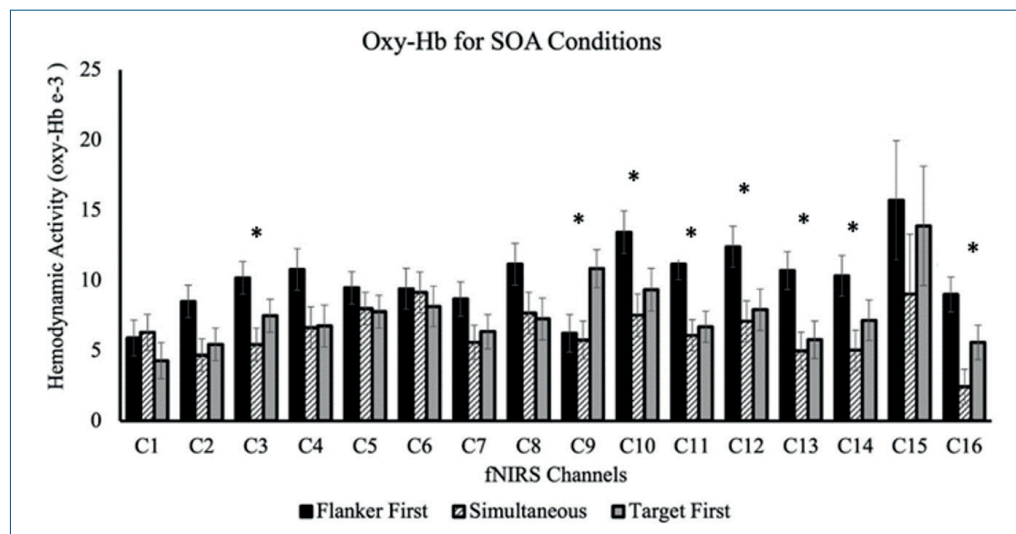


Figure 5. Mean Oxy-Hb (e-3) as a function of stimulus onset asynchrony (SOA) (C1, C2, ...: Channel 1, Channel 2 ... and so on. *: significance at $p < 0.05$ after hierarchical FDR correction; error bars: standard errors).

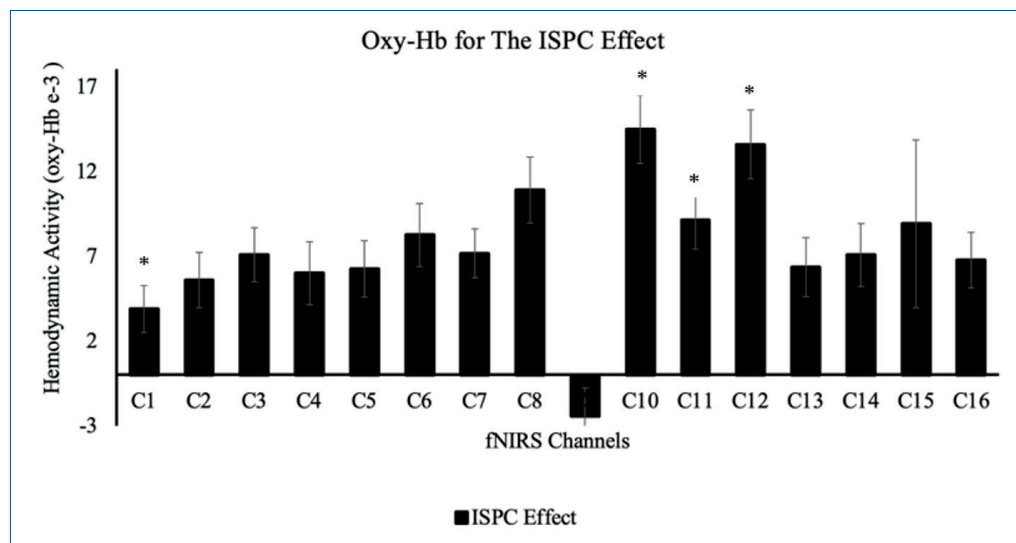


Figure 6. Mean Oxy-Hb (e-3) for the ISPC effect (C1, C2 ...: Channel 1, Channel 2 ... and so on; the ISPC effect denotes the congruency and proportion congruency interaction; *: significance at $p < 0.05$ after hierarchical FDR correction; error bars: standard errors).

The two-way interaction between congruency and PC, namely the *ISPC effect*, was significant in channel 1 ($F(1,35) = 10.98$, $p_{FDR} = 0.024$, $\eta^2_p = 0.239$), channel 10 ($F(1,39) = 12.96$, $p_{FDR} = 0.005$, $\eta^2_p = 0.249$), channel 11 ($F(1,39) = 13.63$, $p_{FDR} = 0.005$, $\eta^2_p = 0.259$), and channel 12 ($F(1,39) = 19.02$, $p_{FDR} = 0.005$, $\eta^2_p = 0.328$). The effect was not significant in the remaining channels (see Figure 6). None of the channels showed a significant main effect of congruency or a significant main effect of PC. The two-way interactions between congruency and SOA and between PC and SOA, as well as the three-way interaction among congruency, PC, and SOA, were not significant in any channel.

As a robustness check, the analysis was also conducted under the more stringent pooled BH-FDR procedure applied jointly to all 112 tests (16 channels $\times$ 7 effects). Under this stricter criterion, the SOA main effect remained significant at channels 11 and 16, and the PC $\times$ Congruency interaction remained significant at channels 10, 11, and 12 (all $p_{FDR-pooled} = 0.022$), demonstrating that the core findings are not dependent on the choice of correction strategy. Notably, channel 11 was the only channel to survive the strictest correction for both the SOA main effect and the PC $\times$ Congruency interaction, identifying it as a convergence point between temporal and item-specific effects in the present design.

Contingency Analysis

As described in the Methods section, the contingency framing is an algebraically equivalent re-parameterization of the same 2×2 (PC $\times$ Congruency) subdesign. The Contingency main effect corresponds to the PC $\times$ Congruency interaction reported above, and the Contingency $\times$ Congruency interaction corresponds to the PC main effect. Accordingly, the same statistics apply under both framings, and no additional tests were conducted.

Under this re-parameterization, the significant PC $\times$ Congruency interaction at channels 1, 10, 11, and 12 is equivalently interpreted as a significant main effect of Contingency: hemodynamic responses were greater for high-contingency items (MC-congruent and MI-incongruent) than for low-contingency items (MC-incongruent and MI-congruent) at these four prefrontal channels. This pattern is consistent with the behavioral contingency main effect and supports the engagement of associative learning processes in the prefrontal cortex during the ISPC task.

Critically, the PC main effect – which under the contingency framing corresponds to the Contingency $\times$ Congruency interaction – was not significant at any channel. This effect did not pass Stage 1 of the hierarchical FDR procedure (Simes-combined $p = 0.120$, $p_{FDR} = 0.280$),

indicating that cortex-wide evidence for this contrast was absent. The Contingency $\times$ Congruency interaction is the test that discriminates between the two competing theoretical accounts: the item-specific control account predicts its presence (heightened control for incongruent items should differentially affect the congruency effect across high- and low-contingency items), whereas the contingency learning account predicts its absence (contingency produces only a main effect on response speed, without modulating the congruency effect). The absence of this interaction at the neural level parallels the behavioral null reported above and extends the reanalysis of Schmidt and Besner (2008,4) to prefrontal hemodynamic responses. Together with the significant Contingency main effect at channels 1, 10, 11, and 12, this pattern provides neural evidence consistent with the contingency learning account of the ISPC effect.

DISCUSSION

Behavioral data in the current experiment suggest that contingency learning is the primary mechanism for the ISPC effect. The first piece of evidence was that contingency showed a main effect (faster RTs for high vs. low contingency items across all SOAs), demonstrating that the contingency learning mechanism impacts performance generally. The second piece of evidence was that congruency and contingency interaction (differential congruency effects for high/low contingency) only emerged in the flanker-first condition (~ 250 ms), but in the opposite direction as predicted by the control account (7). In the flanker-first condition, the congruency effect was larger in high-contingency items compared to low-contingency items (see Figure 4). If the change in congruency has been related to item-specific control (7), one would anticipate an opposite pattern driven by responses to incongruent items, a result which we did not observe. The third piece of evidence is that the change in the ISPC effect due to the SOA manipulation was primarily driven by the responses for mostly congruent items (Figure 3). If the change in the ISPC effect with SOA had been related to item-specific attentional control, one would expect the mostly incongruent items to also be affected, as item-specific control is contingent on these items. The fourth piece of evidence is the two-way interaction between SOA and contingency. Specifically, the contingency effect was more pronounced in the flanker-first condition compared to the simultaneous-presentation condition, but it disappeared in the target-first condition with the exact same SOA-dependent pattern as the ISPC effect. Participants responded more quickly to high-contingency items as they could predict the correct response. These four findings collectively support that the SOA manipulation primarily affects the contingency learning aspect of the ISPC effect. In this context, SOA appears to modulate the relative contributions of learning and control mechanisms. In the flanker-first condition, early distractor access allows contingency learning to bypass effortful control, as evidenced by the effect being driven by congruent trials (Figure 4). In the simultaneous condition (0 ms), both mechanisms can contribute, but the processing window for the distractor dimension is reduced. This probably resulted in reduced ISPC effect compared to the flanker-first condition. In the target-first condition ($+250$ ms), the distractor arrives too late to serve as a useful contingency cue or to trigger item-specific control, and the ISPC effect was not significant. Thus, SOA seems to determine whether performance is modulated by contingency learning or slower, resource-demanding control.

The SOA is not the only determining factor for the underlying mechanism of the ISPC effect. As discussed in earlier studies (3,8), set size also plays a critical role. Specifically, when the set size is small, the contingency learning mechanism becomes more pronounced. In the current study, we used a two-item set design, which may have inclined participants to rely on contingency learning, especially when combined with the suitable SOA conditions. Also, in a methodological review (37), it was suggested that cognitive control should be assessed independently from the proportion-

congruency-inducing context items in order to eliminate the effect of contingency learning and other mechanisms. To do this, researchers are encouraged to add a contingency and proportion congruency unbiased independent item sets (50% congruent) when investigating control in the ISPC effect. This could be applicable in the vocal tasks, but in the current experiment, we used a manual flanker task. Adding an independent item set will also expand the response set, requiring more than four responses. In such a case, participants would need to use more than four fingers, but this may not be practical and increase the cognitive demand substantially. For this reason, using an unbiased set is not practical in the current experiment. In addition to task-related factors, individual differences like depression and anxiety may also affect the item-specific control. While these disorders were not screened in the current study, the within-subject design helps us to reduce the effect of such confounds, since each participant was tested under each condition, as in most ISPC experiments in the literature. Nevertheless, in future studies, screening such conditions would provide more precise data in terms of the underlying mechanisms of the ISPC effect.

The role of stimulus diagnosticity in driving the ISPC effect also warrants consideration (6,8). In our flanker task, both the target and distractor dimensions are equally diagnostic of proportion congruency status; however, only the target is fully diagnostic of the correct response. This asymmetry may partly explain why the ISPC effect disappeared in the target-first condition: once the response-diagnostic target has been identified, the less response-diagnostic distractor exerts minimal influence on response preparation, regardless of its contingency properties. Future research should systematically manipulate stimulus diagnosticity alongside SOA to further clarify how these factors interact in modulating item-specific control and contingency learning. While the behavioral data thus provide a coherent account of how SOA modulates the contingency-driven ISPC effect, the fNIRS data present a more nuanced picture.

Although our behavioral results demonstrated that SOA modulates the ISPC effect, this pattern was not fully replicated in the fNIRS hemodynamic responses. Specifically, under the hierarchical FDR correction, significant SOA main effects were observed in eight channels (3,9–14,16), indicating a broadly distributed prefrontal sensitivity to temporal cue dynamics. However, the critical three-way interaction (SOA $\times$ congruency $\times$ PC) did not reach significance in any channel and did not pass Stage 1 of the hierarchical FDR procedure. Several factors may explain this discrepancy. First, the signal-to-noise ratio (SNR) of fNIRS is lower than that of fMRI, and detecting high-order three-way interactions likely requires a larger sample size. Second, SOA effects may induce transient neural dynamics at a millisecond scale, but the inherently slow nature of the hemodynamic response may make it difficult to detect. Third, the behavioral ISPC effect is probably a result of many neural networks, including the anterior cingulate cortex (ACC), parietal regions, sensory cortices, and motor preparation networks, all of which may be sensitive to SOA. Since our fNIRS coverage was restricted to the prefrontal cortex (PFC), the contribution of these regions may have gone undetected. Fourth, it is also possible that PFC engagement reaches a ceiling effect whenever a distractor is present, regardless of its timing, meaning behavioral differences reflect downstream response preparation rather than variations in PFC recruitment. Although different behavioral processes may dominate depending on the SOA, contingency learning and cognitive control may share overlapping neural substrates within the PFC. This overlap could produce similar and indistinguishable hemodynamic patterns that the current spatial resolution of fNIRS cannot separate. These limitations suggest that while behavioral data clearly show a modulation of mechanisms, the neural correlates may require more sensitive measures to be fully disentangled. Future research should employ larger samples, event-related designs, and multimodal

approaches, such as combined fNIRS-EEG or high-density fNIRS and fMRI, to examine multiple brain regions simultaneously and capture the rapid neural dynamics of the ISPC effect.

Crucially, while behavioral results support contingency learning, the fNIRS data reveal ISPC-related hemodynamic modulation in specific prefrontal channels. The PC analysis showed the ISPC effect in channels 1, 10, 11, and 12 after hierarchical FDR correction; under the contingency framing, these same channels equivalently show a significant main effect of Contingency. According to the manufacturer's Brodmann area mapping (26–28,38), channel 1 maps to BA 46 and BA 10, whereas channels 10, 11, and 12 map to the BA 10/BA 11 overlap zone. This spatial dissociation is noteworthy: the ISPC effect emerged in a lateral channel with BA 46 sensitivity and in medial channels with BA 11 sensitivity, but not in the remaining channels. Channel 1's BA 46 involvement is broadly consistent with earlier fMRI research implicating dorsolateral prefrontal regions in proportion congruency effects (13,14). The BA 11 sensitivity of channels 10–12, on the other hand, is consistent with the involvement of anterior prefrontal regions that have been implicated in stimulus–reinforcement association learning and in evaluating the predictive value of stimuli (39–41) processes closely related to the contingency learning mechanism proposed for the ISPC effect. Notably, the PC main effect – which under the contingency framing corresponds to the theoretically critical Contingency $\times$ Congruency interaction – was not significant at any channel and did not pass the effect-level screening stage of the hierarchical FDR procedure. This null result parallels the behavioral finding and is consistent with the contingency learning account (4). Additionally, channel 11 was the only channel to show a significant effect for both SOA and the ISPC effect under the most stringent correction (pooled FDR across all 112 tests), identifying it as a candidate convergence point for temporal and item-specific processing in the anterior medial prefrontal cortex. However, it should be noted that BA 10 is common to all significant channels and spans nearly the entire sensor, limiting its interpretive specificity. Moreover, because BA 11 extends onto the ventral orbital surface, which folds behind the eyes and is largely inaccessible to surface-mounted fNIRS optodes, the present data cannot confirm whether the activation reflects the orbitofrontal cortex per se or the adjacent rostral prefrontal cortex. The precise cortical loci should be confirmed by future studies using individual-level anatomical co-registration, optode digitization, or higher-density fNIRS arrays. Together, these results suggest that prefrontal regions with sensitivity to both BA 46 and BA 11 show ISPC-related hemodynamic modulation, which is consistent with the possible involvement of both control and learning processes, though the spatial resolution of the present montage does not permit definitive functional–anatomical attribution.

It is worth noting that mechanisms other than contingency learning and item-specific control may contribute to the ISPC effect. One such mechanism is response priming/repetition. According to this mechanism, items sharing the same response or repeating stimulus features across consecutive trials (e.g., the letter 'F' appearing in both trial n and trial $n+1$) can facilitate response speed (42). Consequently, in ISPC experiments, high contingency items would be more likely to benefit from these repetitive patterns, possibly contributing to the ISPC effect. Although our randomized trial presentation may reduce the contribution of this mechanism, it may not have entirely eliminated it. Another potential contributor is the Congruency Sequence Effect (CSE), which refers to the reduction of the congruency effect following an incongruent trial relative to a congruent one. Given the nature of the task, this mechanism might indirectly influence the ISPC effect (43,44). While our findings support that contingency-related processes are robustly involved, it is not possible to completely rule out the influence of other mechanisms.

Overall, this study contributes to the literature by integrating behavioral methods with fNIRS imaging to investigate the mechanisms underlying the ISPC effect. By combining temporal manipulation (SOA) with prefrontal hemodynamic measurement, the present findings offer initial neuroimaging evidence suggesting that contingency learning and item-specific control may operate as complementary rather than competing processes.

To conclude, together, the behavioral and fNIRS data are consistent with the view that contingency learning and cognitive control are not necessarily antagonistic processes; rather, they may operate as complementary mechanisms whose relative contributions are modulated by temporal parameters such as SOA. While the current findings cannot definitively rule out alternative explanations, they provide converging behavioral and neuroimaging evidence supporting a multifactorial account of the ISPC effect.

Ethics Committee Approval: The study was conducted in accordance with the Declaration of Helsinki, and the procedure was approved by the Ethics Committee of the Izmir University of Economics (B.30.2.IEÜ.0.05.05–020–052, Date: 07.04.2017).

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