

# **Exploration of the Mechanisms Underlying the ISPC Effect: Evidence from Behavioral and Neuroimaging Data**

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## **Abstract**

The item-specific proportion congruent (ISPC) effect in a Stroop task – the observation of reduced interference for color words mostly presented in an incongruent color – has attracted growing interest since the original study by Jacoby [1]. Two mechanisms have been proposed to explain the effect: associative learning of contingencies and item-specific control through word reading modulation. Both interpretations have received empirical support from behavioral data. Therefore, the aim of this study was to investigate the responsible mechanisms of the ISPC effect with the classic two-item sets design using fMRI. Results showed that the ISPC effect is associated with increased activity in the anterior cingulate (ACC), dorsolateral prefrontal (DLPFC), and inferior and superior parietal cortex. Importantly, behavioral and fMRI analyses specifically addressing the respective contribution of associative learning and item-specific control mechanisms brought support for the contingency learning account of the ISPC effect. Results are discussed in reference to task and procedure characteristics that may influence the extent to which item-specific control and/or contingency learning contribute to the ISPC effect.

**Keywords:** Stroop task, Item-specific proportion congruent effect, fMRI, Cognitive control, Associative learning

## 1. Introduction

Cognitive control refers to our ability to flexibly adjust our behavior depending on situational demands and changes in the environment. Cognitive control processes are typically assumed to be involved in situations where we have to restrain a predominant or instantaneous response in order to promote a more appropriate but less obvious and salient response. One of the most widely used paradigms in the study of cognitive control is the classic Stroop task [2]. In common variants of this task, participants must indicate the color that a word is printed in, while ignoring the meaning of the word. In incongruent trials, there is a mismatch between the color of the stimulus and the color word, such as the word *red* printed in green ink. Such stimuli require participants to select between competing naming and reading responses, unlike congruent stimuli such as the word *red* printed in red ink.

Different effects have been associated with the Stroop task. First of all, the interference effect consists in slower or less accurate responses for incongruent items than for congruent or neutral items. Interestingly, despite the low complexity of task instructions, the interference effect is a very robust phenomenon observed in hundreds of studies [3]; it is explained by the automaticity and speed of the reading process once it has been fully acquired [4, 5]. The facilitation effect, on the other hand, corresponds to faster or more accurate responses for words printed in a congruent color than for neutral items. As with the interference effect, facilitation occurs when participants rely on the well-practiced word reading process rather than on color naming [5, 6]. Together, interference from incongruent trials and facilitation from congruent trials represent the Stroop effect. Finally, other effects have also been associated with the Stroop task in the literature, namely the proportion congruent effect and the item specific proportion congruent (ISPC) effect, which will be discussed in the following sections.

### *1.1. The Proportion Congruent Effect*

The proportion congruent effect reflects the observation of smaller interference and facilitation effects in tasks characterized by the presentation of mainly incongruent items [e.g., 7, 8, 9]. This effect has traditionally been studied at a global or list-wide level by comparing performance on congruent and incongruent blocks, namely blocks containing a majority of congruent or incongruent items, respectively [10, 11]. The standard interpretation of this phenomenon postulates that the inhibition of the word reading process varies depending on task context [e.g., 9, 12], with a decreased influence of the word reading process for all the items (congruent and incongruent) presented during mostly incongruent blocks compared to mostly congruent blocks.

The Dual Mechanisms of Control model [DMC; 13, 14, 15] explains the modulation of word reading according to task context by proposing the existence of two separate cognitive control mechanisms. In situations of high interference (when mainly incongruent items are presented), subjects would adopt a proactive strategy, which is an anticipatory and sustained form of attention, where goal-relevant information is highly activated (i.e., naming colors rather than reading words). Conversely, in a situation where interference is less frequent, participants would adopt a reactive control strategy, which consists in a late correction strategy, where attentional control is recruited only when needed, such as after the occurrence of an interfering item in a block where interference is rare.

### *1.2. The Item-Specific Proportion Congruent (ISPC) Effect*

In the last decade, the proportion congruent effect has also been observed at a more local level, when specific stimuli, rather than blocks of stimuli, are associated with high or low conflict (e.g., the stimulus *red* appearing in red ink 20% vs. 80% of the time). Again, smaller interference and facilitation effects for color words that were mainly presented in an incongruent color compared to color words usually presented in a congruent way have been reported [1, 16].

In their original study, [1] noted that two dissociable interpretations could account for the ISPC effect. First, the modulation interpretation (modulation or item-specific control hypothesis) considers that cognitive control might prevent full reading of words just after stimulus presentation. Specifically, as proposed by Jacoby and colleagues [1, 17, 18], a word-reading filter would decrease the activation of irrelevant word dimensions as soon as the item is identified with a high probability of being incongruent. As a consequence, word reading processes would have a decreased influence on the response to provide. Second, an associative mechanism (associative learning or contingency hypothesis) could intervene,

whereby participants would rapidly learn the stimulus-response (S-R) associations specific to each item (e.g., the word *red* is often presented in red, whereas the word *blue* is often presented in green). This color-word association would be the main determinant of the response [19], independently of any processes (e.g., inhibitory processes) controlling the contribution of word reading.

Importantly, in Schmidt and Besner's (2008) view, the interpretation of the ISPC effect in terms of cognitive control is due to a general confound in the literature between proportion congruency (proportion of congruent items within a condition) and contingency (degree of S-R association for a given item). More specifically, this confound comes from classically comparing high- versus low-contingency trials within the same proportion congruence condition (e.g., high-contingency congruent items with low-contingency incongruent items in the high proportion congruent condition) rather than directly comparing equivalent contingency trials (e.g., high-contingency congruent trials from the high proportion congruent condition with high-contingency incongruent trials from the low proportion congruent condition, and similarly for low-contingency trials). In their reanalysis of the data from Jacoby et al. (2003), Schmidt and Besner neutralized that confound by reorganizing the data and conducting a contingency by item type (or congruency) analysis. According to the authors, both the contingency and modulation hypotheses predict a main effect of trial type (congruent, incongruent), with longer reaction times for incongruent trials, and a main effect of contingency (high, low), with longer reaction times for low contingency trials. However, they differ concerning the interaction between these factors. Within the contingency hypothesis, it is assumed that the Stroop effect and the contingency effect act independently (i.e., the difference between congruent and incongruent trials would not be expected to vary by contingency). Within the modulation hypothesis, "incongruent trials should be more affected by attention, given that the majority of the Stroop effect is due to interference, with little or no facilitation from congruent trials" (Schmidt & Besner, 2008, p. 516). Hence, this interaction is predicted, with a smaller Stroop effect for high than low contingency items, if attentional control mechanisms are selectively engaged to override word reading in the case of high contingency incongruent words. In that regard, the results of that reanalysis showed an absence of interaction, indicating that contingency information was enough to explain the ISPC effect.

### *1.3. Item-specific control mechanisms and proportion congruent effect at the list level*

Importantly, some authors have recently proposed that item-specific control mechanisms, rather than variations in control strategy at the list-wide level, may also account

for the proportion congruent effect at the global or list level [16, 20, 21]. Indeed, in typical list-wide proportion congruency experiments, variations in list-wide proportion congruency are confounded with variations in item-specific proportion congruency. For example, in a mostly incongruent bloc (80 % of incongruent trials), all the items of the stimulus set (e.g., the words *Black*, *Blue*, *Green*, and *Red*) appear in an incongruent form for 80% of the trials and in a congruent form for 20 % of the trials. Hence, a control mechanism acting at the item-specific level can account alone for the list-wide proportion congruency effect. In that context, Bugg et al. (2008) recently unconfounded list-wide and item-specific proportion congruency and obtained data supporting the hypothesis that list-wide effects can be accounted for by item-specific mechanisms (see also Blais & Bunge, 2010, for similar findings). However, other recent studies provided evidence of the involvement of list-level control mechanisms when item-specific influences were controlled for [22-24]. Hence, even if item-specific control mechanisms may be partly responsible of the list-wide proportion congruency effect, it seems too early to dismiss any contribution of list-wide control mechanisms modulating the influence of word reading processes.

### *1.3. Neuroimaging of Proportion Congruent and ISPC Effects in the Stroop Task*

Studies that have attempted to determine the brain areas associated with interference resolution in the Stroop task have consistently reported the involvement of a large fronto-parietal network involving the dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), inferior frontal gyrus, and parietal cortex [25-27]. Within this network and in accordance with the conflict monitoring hypothesis [28, 29], the detection of conflicts in information processing occurs in the ACC, which informs and recruits the DLPFC to resolve the conflict between incompatible response tendencies by making strategic adjustments in cognitive control. Importantly, within Botvinick's model, the ACC-DLPFC network is assumed to be very sensitive to the global amount of conflict within a block or list of stimuli. Neural evidence supporting that prediction comes from studies showing higher ACC activation for incongruent (in comparison to congruent) items in a mostly congruent list but not in a mostly incongruent one, in which case there was no differential activation of that area for incongruent and congruent items [30, 31].

At this time, only one previous study has explored the neural substrates associated with the ISPC effect. In a functional magnetic resonance imaging (fMRI) study, [20] recently demonstrated that the ACC-DLPFC network was strongly engaged when proportion congruency was manipulated at the level of specific items. In their view [see also 21], cognitive control, in situations of proportion congruency manipulation, can be implemented in

the ACC-DLPFC not only at the global level, but also more locally, at the level of individual stimuli. In other words, for Blais and Bunge (2010), the ACC-DLPFC network may thus modulate attention to an item based on local attributes of the task (i.e., the level of conflict associated with this specific item) rather than global attributes (i.e., the level of conflict associated with a list of items).

#### *1.4. Aim of the Study*

The ongoing debate in the literature concerning the mechanism responsible for the ISPC effect has received support from behavioral studies for both the associative learning (Schmidt & Besner, 2008) and item-specific control hypotheses [18, 20]. Surprisingly, and as mentioned above, only one fMRI study has investigated the neural correlates of the ISPC effect (Blais & Bunge, 2010). However, that study only explored whether the ACC-DLPFC network might be sensitive to item-specific proportion congruency manipulation by contrasting brain activity for incongruent and congruent trials. In fact, these authors did not perform the contingency x item type interaction analysis which is, according to Schmidt and Besner (2008), the most appropriate to evaluate the underlying mechanism responsible of the ISPC effect. Therefore, the objective of the present study was to further investigate the neural correlates of the ISPC effect with the classical 2-item sets design. To do this, we used a variant of the Stroop task where two color words were mainly presented in a congruent color (mostly congruent [MC] set) and two color words in an incongruent color (mostly incongruent [MI] set) in order to replicate the well-known ISPC effect (i.e., less interference from incongruent and less facilitation from congruent trials in the MI than the MC set).

Our predictions were as follows. At the behavioral level, we first expected to replicate the ISPC effect, namely a modulation of the Stroop effect size as a function of proportion congruency (larger interference and facilitation effects in the MC compared to the MI set). In addition, we expected to find a significant contingency x item type interaction if the ISPC effect was due to item-specific control, but no interaction if pure associative learning mechanisms were engaged (see Schmidt & Besner, 2008).

At the neuroimaging level, we were first interested in determining whether the ISPC effect observed at the behavioral level was associated with some modulation of the brain activation pattern between the interference effect (incongruent vs. congruent trials) in the mostly congruent and the mostly incongruent set. In addition, we performed the contingency x item type interaction analysis as suggested by Schmidt and Besner (2008). More specifically, if item-specific control underlies the ISPC effect, as argued by Blais and Bunge (2010) in their recent study, the presence of specific brain activity in the ACC-DLPFC network

(reflecting conflict detection and control implementation, respectively) should be observed for the interference effect in low contingency trials (compared to high contingency trials). On the contrary, if associative learning mechanisms underlie the ISPC effect with the classic 2-item sets design, low contingency incongruent trials (compared to low contingency congruent trials) should not elicit specific activations of this ACC-DLPFC network in comparison to high contingency incongruent trials (compared to high contingency congruent trials).

## **2. Material and Methods**

### *2.1. Participants*

Twenty-eight participants from the university community were recruited to take part in this study. All were right-handed French native speakers and had normal or corrected to normal vision (with no color vision or color discrimination deficiencies), and no diagnosed psychological or neurological disorders. The Ethics Committee of the Faculty of Medicine of the University of Liège approved this study. Moreover, and in line with the Declaration of Helsinki, each participant gave his/her written informed consent prior to inclusion in the study and was screened for any physical or medical condition that could rule out fMRI experimentation. In our sample, three participants were excluded from further analysis because of technical problems during scanning or incomplete data acquisition. The 25 remaining participants included 12 men and 13 women. The mean age was  $21.8 \pm 2.68$  years (range: 18 to 29 years).

### *2.2. Stimuli*

Four color words (presented in French) were used in this experiment (*orange*, *yellow*, *gray*, and *mauve*). Each of them was presented in a congruent form (compatibility between ink color and word meaning) and an incongruent form (incompatibility between ink color and word meaning). Neutral items consisted in a nonverbal stimulus, namely a string of five percent signs (%%%) presented in one of the four color possibilities. All the color words and neutral items were presented on a white screen. Color words were divided into two sets: one mostly incongruent (MI) and one mostly congruent (MC) set. In the MI set, the two color words (i.e., *gray* and *yellow*) were presented in an incongruent form 80% of the time (e.g., the word *gray* written in yellow) and in a congruent form 20% of the time (e.g., the word *gray* written in gray). These proportions were reversed for the MC set, where the two color words (*orange* and *mauve*) were presented 80% of the time in a congruent form and 20% of the time in an incongruent form. The assignment of colors to MC or MI set was not counterbalanced across participants. The experiment was divided into 30 blocks of 12 items each, for a total of 360 items. In order to avoid any proportion congruent effect at the list-wide level, each block



contained five congruent, five incongruent, and two neutral items, making it impossible for participants to make inferences about the congruency of the following item. Concerning the item-specific proportion congruency manipulation, four of the five incongruent items of each block were color words from the MI set and one from the MC set; conversely for the five congruent items, four were from the MC set and one from the MI set. The stimulus presentation order was pseudo-randomized across participants, with the use of three different presentation order lists.

### 2.3. Procedure

Participants were told that they would have to select the color in which each item was printed, and were informed that items would be presented briefly. The instruction was to respond as fast and accurately as possible. Participants saw color words on the screen through a mirror located on the scanner's head coil. For each trial, a word was presented in the center of the screen, with four response possibilities at the bottom of the screen corresponding to the first letter (written in brown, a color never used for the items) of the four color ink possibilities. Participants had thus to press one of the four response keys on a keyboard, always in the same order (mauve, yellow, grey, orange, respectively). They used the index and the middle fingers of their left and right hands for responding. Each item was presented for a maximum of 2000 ms or until the participant responded. If the response was given before this deadline, a white screen appeared for the remainder of the 2000 ms. If there was no response, the screen flashed white after 2000 ms and an interstimulus interval of 500 ms was presented prior to the next item. Breaks were provided during the experiment; they consisted in a fixation cross on the center of the screen for 5000 ms every two or three blocks.

Participants performed a practice phase outside the scanner prior to the test phase, to ensure that they had properly understood the task instructions. Once in the fMRI scanner, four more examples were presented and then the test phase began.

### 2.4. Behavioral data analysis

At the behavioral level, all analyses were performed with a statistical level of  $p < .05$ . Statistical analyses consisted of repeated measures analyses of variance (ANOVAs) on the mean of reaction times associated with correct responses. The first ANOVA was a 2 (Proportion congruency: MC vs. MI colors) x 2 (Item type: incongruent vs. congruent), and the second ANOVA was a 2 (Contingency: low vs. high) x 2 (Item type: incongruent vs. congruent). The measure of effect size was reported as partial eta squared ( $\eta_p^2$ ). Moreover, post hoc comparisons were performed for all ANOVAs, using pairwise Tukey's tests ( $p <$

.05). Concerning accuracy data analyses, we only compared the number of errors for incongruent items in the MI and MC sets, given the floor effect concerning the error rate for congruent items in both sets (error rates inferior to 2%).

### 2.5. MRI acquisition

Functional MRI time series were acquired on a 3T head-only scanner (Magnetom Allegra, Siemens Medical Solutions, Erlangen, Germany) operated with the standard transmit-receive quadrature head coil. Multislice T2\*-weighted functional images were acquired with a gradient-echo echo-planar imaging sequence using axial slice orientation and covering the whole brain (32 slices, FoV = 220 x 220 mm<sup>2</sup>, voxel size 3.4 x 3.4 x 3 mm<sup>3</sup>, 30% interslice gap, matrix size 64 x 64 x 32, TR = 2130 ms, TE = 40 ms, FA = 90°). For anatomical reference, a high-resolution T1-weighted image (3D MDEFT) was acquired for each subject [32; TR = 7.92 ms, TE = 2.4 ms, TI = 910 ms, FA = 15°, FoV = 256 x 224 x 176 mm<sup>3</sup>, 1 mm isotropic spatial resolution]. The first three volumes were discarded to avoid T1 saturation effects. Head movement was minimized by restraining the subject's head using a vacuum cushion. Stimuli were displayed on a screen positioned at the rear of the scanner, which the participant could comfortably see through a mirror mounted on the standard head coil.

### 2.6. Functional data analyses

Data were preprocessed and analyzed using SPM8 (Wellcome Department of Imaging Neuroscience, <http://www.fil.ion.ucl.ac.uk/spm>) implemented in MATLAB 7.5.0 (Mathworks Inc., Sherborn, MA). Images of each individual participant were first realigned (motion corrected). After this realignment, we spatially coregistered the mean EPI image to the anatomical MRI image and coregistration parameters were applied to the realigned BOLD time series. Individual anatomical MRIs were spatially normalized into MNI space (Montreal Neurological Institute, <http://www.bic.mni.mcgill.ca>) and the normalization parameters were subsequently applied to the individually coregistered BOLD times series, which was then smoothed using an isotropic 8-mm full-width at half-maximum (FWHM) Gaussian kernel.

For each participant, BOLD responses were modeled at each voxel, using a general linear model with events as regressors. Events were modeled according to the set of item (MC or MI set) and the type of item (Incongruent, congruent, or neutral). These 6 regressors were modeled as event-related responses. Event durations corresponded to the presentation of the item until the subject's response, with a maximum duration of 2 s. Each event was convolved with a canonical hemodynamic response function. Incorrect trials and no responses were also modeled as separate regressors. The design matrix also included the realignment parameters to account for any residual movement-related effect. A high pass filter was implemented

using a cut off period of 256 s in order to remove the low frequency drifts from the time series. Linear contrasts estimated the simple main effect of each trial type. The resulting set of voxel values constituted a map of  $t$  statistics SPM[T]. The corresponding contrast images were smoothed (6-mm FWHM Gaussian Kernel) and entered into a second-level analysis, corresponding to random-effect model. All analyses were conducted using a correction for multiple comparisons at the voxel level with a conservative family-wise error (FWE) threshold  $p < .05$ . A 2 (Set: MC vs. MI) x 2 (Item type: incongruent vs. congruent) whole-brain voxel-wise repeated measures ANOVA was performed, which allowed us to examine the brain regions related to the comparisons of interest (i.e., general interference effect in both sets, comparison of incongruent related activity between sets, incongruent vs. congruent trials within each set). Finally, the proportion congruency x item type and the contingency x item type interactions analyses were conducted in order to investigate specific brain activations related (1) to the interference effect in the MC set (compared to the MI set) and (2) to the interference effect for low contingency trials (compared to high contingency trials), respectively. All activations with a  $p$  FWE  $< .05$  were reported.

### 3. Results

#### 3.1. Behavioral data

##### 3.1.1. ISPC Effect

A 2 (Proportion congruency: MI vs. MC) x 2 (Item type: incongruent vs. congruent) repeated measures ANOVA was conducted on the mean of response times for correct responses (see Figure 1a). This analysis showed no main effect of set ( $F(1,24) = 0.61$ ;  $p = .44$ ;  $\eta_p^2 = .02$ ), indicating that reaction times were globally similar for the two sets, but a main effect of item type ( $F(1,24) = 216.04$ ;  $p < .0001$ ;  $\eta_p^2 = .90$ ), showing globally longer reaction times for incongruent items than for congruent items. Moreover, the set x item type interaction was statistically significant ( $F(1,24) = 55.24$ ;  $p < .0001$ ;  $\eta_p^2 = .70$ ).

INSERT FIGURE 1 HERE

Tukey post hoc comparisons showed interference (incongruent vs. congruent) for both the MI and MC (both  $ps < .001$ ) sets of colors (see figure 1a). More importantly, reaction times were slower for incongruent items and faster for congruent items in the MC versus the

MI set (both  $ps < .001$ ). These results showed the presence of the expected ISPC effect, namely the expected modulation of Stroop effect size as a function of proportion congruency.

Concerning accuracy data (percentage of errors and no response), we evidenced a larger number of errors for incongruent items in the MC than in the MI set ( $t(48) = -3.74; p < .001$ ), which is in agreement with the ISPC effect. A summary of accuracy data is presented in Table 1.

INSERT TABLE 1 HERE

### *3.1.2. Contribution of Associative Learning*

To determine the respective contributions of associative learning versus cognitive control to the ISPC effect, we performed the contingency by item type analysis proposed by Schmidt and Besner (2008). The 2 (Contingency: high vs. low) x 2 (Item type: incongruent vs. congruent) repeated measures ANOVA on the mean of response times for correct responses revealed a main effect of contingency ( $F(1,24) = 55.24; p < .0001; \eta_p^2 = .70$ ), and of item type ( $F(1,24) = 216.04; p < .0001; \eta_p^2 = .90$ ), but no interaction ( $F(1,24) = 0.61; p = .44; \eta_p^2 = .02$ ; see Figure 1b).

## *3.2. fMRI Data*

### *3.2.1. General interference effect*

The change in neural activity was compared for incongruent and congruent items, independently of the set of colors. This general interference effect in MC and MI sets activated the classic fronto-parietal network associated with conflict resolution in the Stroop literature, with increased activity especially in the DLPFC, and inferior parietal lobule. However, ACC activity was found only at a  $p < .001$  uncorrected statistical level (MNI peak: [-8, 24, 42];  $Z = 4.16$ ). Details of these patterns of brain activity are presented in table 2.

INSERT TABLE 2 HERE

### *3.2.2. ISPC effect*

When incongruent-item-related activity was compared in the MC and MI sets, the network of brain areas revealed by this contrast evidenced cingulate, parietal and prefrontal

activations (see Table 3a and Figure 2). The reverse contrast (incongruent items in MI vs. MC) did not reveal any significant increase in activity (Table 3b).

INSERT TABLE 3 AND FIGURE 2 HERE

Similar results were obtained when we contrasted the incongruent and congruent items in the MC set, with increased activity in the same large fronto-parietal network (Table 4a) for incongruent items. Moreover, contrasting incongruent and congruent items in the MI set did not reveal any differential change in brain activity (Table 4b).

INSERT TABLE 4 HERE

Finally, the proportion congruency x item type interaction ((incongruent vs. congruent items in MC set) – (incongruent vs. congruent items in MI set)) confirmed that a network of areas including the cingulate, frontal and parietal regions is specifically associated with the processing of incongruent items in the mostly congruent set only (see Table 5a and Figure 3).

As a whole, although this pattern of results (i.e., activation of the ACC-DLPFC network at the item level) is in agreement with the item-specific control hypothesis, it does not allow us to definitively conclude that item-specific control mechanisms underlie the ISPC effect. Indeed, as argued by Schmidt and Besner (2008), these analyses confound proportion congruency with contingency. In the next section, we therefore conducted a contingency x item type interaction analysis to better assess the possible involvement of associative learning mechanisms in the ISPC effect.

INSERT TABLE 5 AND FIGURE 3 HERE

### *3.2.3. Contribution of associative learning versus item-specific cognitive control*

As mentioned in our hypotheses, item-specific control and contingency learning accounts do not predict the same pattern of results concerning the contingency x item type interaction ((incongruent in MC set vs. congruent in MI set) – (incongruent in MI set vs. congruent in MC set)). More specifically, specific foci of brain activity, especially in the ACC-DLPFC network, were expected within the item-specific control view, but not within the contingency view in which the interaction was expected to be non significant. In this context, this interaction failed to evoke any significant activation at the statistical threshold

used (FWE,  $p < .05$ ), supporting thus the role of associative learning mechanisms in the ISPC effect (see Table 5b).

We also compared high contingency (incongruent items of MI set and congruent items of MC set) to low contingency trials (congruent items of MI set and incongruent items of MC set) in order to reveal regions that support S-R learning in this paradigm. This analysis only revealed a medial frontal activation at a  $p < .001$  uncorrected  $p$  threshold (MNI peak: [-12 58 8];  $Z = 3.34$ ).

#### **4. Discussion**

Previously, support for both the item-specific control and the associative learning explanations of the ISPC effect had been found at the behavioral level [e.g., 18, 33]. At the brain level, the only existing study of Blais and Bunge (2010) evidenced that the ACC-DLPFC network, conceived as responsible for conflict detection and control implementation, was sensitive to item-specific proportion congruency manipulation. In this context, the present study aimed to further investigate neural correlates of the ISPC effect using the contingency x item type interaction analysis, with the classical 2-item sets design.

##### *4.1. Replication of the ISPC Effect*

At the behavioral level, we replicated the now well-established ISPC effect, showing that the classic proportion-congruent effect, typically investigated at the list level by presenting blocks of stimuli varying the proportion of congruent and incongruent trials (Bélanger et al., 2010; Kane & Engle, 2003), can arise when proportion congruency is manipulated at the item level. More specifically, interference and facilitation effects were larger in the MC than in the MI set of colors.

With regard to neuroimaging data, we observed incongruent item-related activity in the ACC, DLPFC and inferior parietal cortex in the MC set. These areas correspond to the brain network typically associated with cognitive control during conflict resolution and the proportion congruent effect at the global level in the Stroop task (Carter et al., 2000; Laird et al., 2005; Nee et al., 2007; Roberts & Hall, 2008). In line with the recent study by Blais and Bunge (2010), the results obtained here showed that brain regions classically associated with conflict resolution at a global level, specifically the ACC (detection of conflict) and DLPFC (adjustments in cognitive control), which have been argued to implement list-level effects (Botvinick et al., 2001), can also be recruited when manipulation of congruency proportion occurs at the level of specific items.

#### *4.2. The Mechanism Responsible for the ISPC: Associative Learning or Item-Specific Control?*

As mentioned above, an important issue currently being debated in the literature concerns the underlying mechanisms responsible for the ISPC effect. Two possible candidates have been proposed: control and associative learning mechanisms [e.g., 18]. This has led some authors to adopt a strict associative learning conception of the ISPC effect (Schmidt & Besner, 2008), whereas others consider that both item-specific control and contingency learning (learning of S-R associations) may contribute to the effect [1, 18].

Concerning behavioral data, the contingency x item type analysis on mean reaction times did not evidence any significant interaction. According to Schmidt and Besner (2008), the associative learning hypothesis states that the Stroop effect (effect of congruency: difference between incongruent and congruent trials) and the contingency effect (predictability of color-word associations) reflect distinct processes, and their joint action has an additive rather than an interactive effect on performance. So, our results related to response times are in agreement with the associative learning explanation.

With regard to neuroimaging data, the contingency x item type interaction analysis did not reveal any significant activation, and thus argued also in favor of associative learning mechanisms as responsible for the ISPC effect. Hence, the ACC-DLPFC network that we observed using the classical proportion congruency x item type interaction did not emerge in this interaction. This finding is consistent with Schmidt and Besner (2008) view, and supports the idea that the activation level of the ACC-DLPFC network for incongruent compared to congruent trials does not vary as a function of contingency.

As a consequence, if item-specific control is not the mechanism responsible for the ISPC effect, one may ask what is the exact role of the fronto-parietal activations that we observed. Indeed, these brain regions are classically associated with conflict detection and subsequent implementation of cognitive control [25, 27]. In this line, these regions may be involved in detection and subsequent processing of unanticipated stimuli. Indeed, whereas events of similar frequency (low contingency) were contrasted in the first term of the contingency x item type interaction (incongruent trials of MC set to congruent trials of MI set), rare events (low contingency incongruent trials of the MC set) were contrasted to frequent events (high contingency congruent trials of the MC set) in the first term of the classical proportion congruency x item type interaction. Therefore, brain activity observed in the last contrast may reflect processing of unexpected or rare stimuli which did not respect previously learned S-R associations [34]. Indeed, [35] have argued that the role of the ACC

was not limited to conflict detection. In their error-likelihood hypothesis, they proposed that this region may be involved in predicting error likelihood in a given context. In other words, this region would be more activated for events potentially associated with a higher perceived probability of error (i.e., low contingency trials). Hence, the observed ACC activation in the proportion congruency x item type interaction may reflect the higher error prediction for low contingency (incongruent trials of MC set) compared to high contingency trials (congruent trials of MC set). Concerning the DLPFC, several studies have shown that this region is involved in contingency information processing [e.g., 36, 37]. Specifically, the DLPFC supports the acquisition of new S-R associations and plays a major role by selecting the appropriate response to unexpected stimuli. Moreover, [38] argued that the parietal cortex is responsible for representing the possible candidate responses by maintaining the different S-R associations activated in working memory, whereas the prefrontal cortex is recruited for the acquisition of new S-R associations and for interference resolution after conflict detection by the ACC (e.g., Blais et al., 2007; Botvinick et al., 2001). In this regard, parietal activation observed in the proportion congruency x item type interaction analysis could reflect the need to maintain simultaneously active the different possible S-R associations for low-contingency items in comparison to high-contingency ones, for which the need to activate the two S-R associations simultaneously is strongly reduced, one of those two contingencies being enough to correctly respond in 80% of the trials for that color word.

In this context, if these brain areas are involved in detecting and processing unexpected events, one may wonder why we failed to evidence any differential brain activation in the MI set between low expectancy congruent trials and high expectancy incongruent trials (data not showed). A possible explanation may be related to the fact that, in this case, the unexpected trial type is congruent. Signals regarding potential errors may be less robust due to the ease in processing these trials, even if they still violate expectancy.

Finally, our analysis directly comparing high contingency trials (incongruent items of MI set and congruent items of MC set) to low contingency trials (incongruent items of MC set and congruent items of MI set) also brought some support to the contingency hypothesis. Indeed, this comparison revealed (at an uncorrected statistical  $p$  level) activity in a medial frontal area that may play a role in S-R learning and response prediction processes.

In conclusion, and in agreement with the proposal of Schmidt and Besner (2008), our results underline the importance of performing the contingency x item type interaction analysis when investigating the neural correlates of ISPC effect. Indeed, although our results evidenced an ACC-DLPFC network activation in the classical analyses (e.g., the proportion



congruency x item type interaction), the contingency x item type interaction failed to reach significance, supporting thus the contingency learning account.

As a whole, results of the present experiment showed that the ISPC effect (i.e., the attenuated interference for mostly incongruent compared to mostly congruent items) was better explained within the contingency view of the phenomenon. However, we cannot definitively rule out the possible intervention of item-specific control mechanism in the ISPC effect. Indeed, behavioral data have shown that the degree to which associative learning and/or item-specific control intervene depend on task and procedure characteristics. In this context, [18] recently demonstrated that a critical factor determining the responsible mechanism is the dimension that serves as ISPC signal (i.e., which dimension constitutes the signal that directs all subsequent processing). Specifically, they showed, using a picture-word Stroop paradigm, that contingency could not account for the ISPC effect when the relevant dimension (i.e., the picture) was used as the ISPC signal, but this was not the case when the irrelevant dimension was used as ISPC signal (i.e., word name). In that line, the present study used the classic color-word Stroop procedure, which, in their view, promotes the use of contingency learning given that this procedure favors the use of the word dimension as ISPC signal [see also 24]. In addition, the present study used the classic two-item sets design of ISPC effect originally used by Jacoby et al. (2003). In this design, one set of items (i.e., *gray* and *yellow*) is presented in mostly incongruent form (*gray* in yellow, *yellow* in gray) while the other set (i.e., *mauve* and *orange*) is presented in mostly congruent form (*mauve* in mauve, *orange* in orange). This set size has been argued to promote contingency learning (e.g., respond “yellow” when the word is *gray*) rather than item-specific control [22, 23, 33]. Indeed, [39]Bugg and Hutchison (in press) recently showed a contingency-driven ISPC effect with the classical 2-item sets design, but a control-driven ISPC effect when a 4-item sets design was employed. Therefore, using 4-item rather than 2-item sets may be helpful in disentangling the contribution of both processes. Indeed, in this case, relying on contingency learning would be less reliable since the incongruent items in the mostly incongruent set are associated with three responses with a similar degree of contingency contrary to the single high-contingency response in the 2-item sets design. Understanding which experimental conditions elicit and favor the differential involvement of the ACC-DLPFC network between low and high proportion congruency trials (item-specific control) is undoubtedly a crucial issue for further research.

## **5. Conclusions**

This study is the first fMRI experiment that evaluated predictions derived from the item-specific control and associative learning accounts of ISPC effect. Together, the behavioral and fMRI results revealed the involvement of contingency learning mechanisms in the ISPC effect, as argued by Schmidt and Besner (2008). However, further neuroimaging studies are necessary to confirm any contributions of item-specific control in the ISPC effect in general, since task and procedure characteristics appear to influence the extent to which item-specific control and/or associative learning mechanisms are involved in the ISPC effect.

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### **Figure legends**

**Figure 1.** (a) Mean of reaction times (ms) in the MI and MC color sets for incongruent and congruent items. The item specific proportion congruent effect corresponds to faster reaction times for incongruent items and slower ones for congruent items in the MI set compared to the MC set. (b) Absence of interaction between congruency and contingency for reaction time data. Error bars represent standard deviations.

**Figure 2.** Larger brain responses for incongruent trials in the MC than in the MI set (Table 3) in inferior parietal cortex (left), inferior frontal cortex (middle), and anterior cingulate cortex (right). Functional statistical results are overlaid to a canonical structural image ( $p < .05$  FWE corrected). Bar graphs illustrate the mean parameter estimates displayed for the different item types (incongruent and congruent) of both sets. Error bars represent standard errors.

**Figure 3.** Proportion congruency x item type interaction (incongruent vs. congruent in MC set) – (incongruent vs. congruent in MI set) revealing specific cerebral activations for incongruent trials in the MC set ( $p < .05$  FWE corrected).

Table 1

*Accuracy data (percentage of errors and no responses) in MC and MI sets for incongruent and congruent items.*

	<b>MI set</b>	<b>MC set</b>
Incongruent	5.60 (2.79)	11.33 (7.14)
Congruent	1.86 (2.90)	1.23 (1.34)

*Note:* Numbers in parentheses correspond to standard deviations.

Table 2

*Cerebral areas associated with the general interference effect (incongruent vs. congruent) in MC and MI sets.*

Hemisphere	Anatomical region	MNI coordinates			Z score	p value
		x	y	z		
L	Inferior parietal	-38	-44	46	4.78	<b>.012</b>
L	Inferior frontal	-54	16	36	4.96	<b>.005</b>
L	Middle frontal	-48	4	48	4.47	<b>.041</b>
L	Inferior frontal	-44	12	28	4.69	<b>.017</b>
L	Fusiform gyrus	-40	-50	-22	4.88	<b>.008</b>
L	Fusiform gyrus	-36	-64	-18	4.44	<b>.047</b>
L	Inferior occipital	-40	-84	-18	4.58	<b>.026</b>

L = left; R = right; x, y, z: coordinates (mm) in the stereotactic space defined by the Montreal Neurological Institute (MNI). This analysis was conducted with a  $p$  value  $< .05$  FWE corrected.



Table 3

*Cerebral areas associated with the ISPC effect: Brain activity related to incongruent items*

Hemisphere	Anatomical region	MNI coordinates			Z score	p value
		x	y	z		
<b>a) Incongruent items in MC set versus incongruent items in MI set</b>						
R	Inferior parietal	38	-40	36	5.20	<b>.002</b>
L	Inferior Parietal	-38	-46	46	5.07	<b>.003</b>
R	Precuneus	14	-64	48	4.44	<b>.046</b>
L	Inferior frontal	-40	6	30	4.91	<b>.007</b>
L	Inferior frontal	-34	34	26	5.03	<b>.004</b>
R	Inferior frontal	50	14	20	4.74	<b>.013</b>
L	Middle frontal	-42	46	12	4.42	<b>.049</b>
R	Superior frontal	22	-4	48	4.75	<b>.013</b>
R	Anterior cingulate	10	10	44	4.54	<b>.031</b>
<b>b) Incongruent items in MI set versus incongruent items in MC set</b>						
Nihil						

L = left; R = right; x, y, z: coordinates (mm) in the stereotactic space defined by the Montreal Neurological Institute (MNI). This analysis was conducted with a  $p$  value  $< .05$  FWE corrected.

Table 4

*Cerebral areas associated with the ISPC effect: Brain activity related to incongruent versus congruent items in MC and MI sets.*

Hemisphere	Anatomical region	MNI coordinates			Z score	p value
		x	y	z		
<b>a) Incongruent versus congruent items in MC set</b>						
L	Inferior parietal	-36	-48	48	7.43	< .001
L	Superior parietal	-24	-66	52	6.03	< .001
R	Inferior parietal	38	-40	38	6.03	< .001
R	Superior parietal	32	-58	52	5.66	< .001
R	Superior parietal	50	-28	52	5.50	< .001
L	Inferior frontal	-46	16	30	7.07	< .001
L	Inferior frontal	-34	32	26	6.20	< .001
R	Inferior frontal	50	14	20	5.66	< .001
R	Middle frontal	28	8	46	5.20	.002
R	Middle frontal	36	38	32	5.29	.001
L	Inferior frontal	-46	16	-8	5.31	.001
L	Insula	-34	22	4	5.64	<.001
R	Insula	36	16	-6	5.50	<.001
L	Middle frontal	-50	44	10	4.93	.006
R	Superior frontal	12	6	66	4.84	.009
R	Superior frontal	22	-4	48	5.21	.002
R	Anterior cingulate	8	12	48	4.99	.005
L	Anterior cingulate	-6	20	44	5.05	.004
R	Fusiform gyrus	40	-68	-18	5.40	.001
R	Inferior temporal	52	-60	-24	4.81	.01
L	Inferior temporal	-48	-50	-18	5.52	< .001
L	Fusiform gyrus	-36	-64	-18	5.38	.001
L	Fusiform gyrus	-40	-80	-18	5.49	<.001
R	Middle occipital	38	-90	0	4.73	.015
L	Middle occipital	-38	-90	-4	4.79	.011
<b>b) Incongruent versus congruent items in MI set</b>						
Nihil						

L = left; R = right; x, y, z: coordinates (mm) in the stereotactic space defined by the Montreal Neurological Institute (MNI). This analysis was conducted with a  $p$  value < .05 FWE corrected.

Table 5

*Cerebral areas associated with the proportion congruency x item type and the contingency x item type interaction analyses.*

Hemisphere	Anatomical region	MNI coordinates			Z score	p value
		x	y	z		
<b>a) Proportion congruency x item type interaction</b>						
<b>(incongruent vs. Congruent in MC set) – (incongruent vs. congruent in MI set)</b>						
L	Inferior Parietal	-36	-46	44	6.07	< .001
L	Superior Parietal	-26	-66	52	4.54	.032
L	Superior Parietal	-36	-56	58	5.04	.004
L	Inferior frontal	-36	34	26	5.84	< .001
L	Inferior frontal	-46	16	30	5.65	< .001
L	Inferior frontal	-34	6	24	5.67	< .001
R	Inferior parietal	40	-40	36	5.73	< .001
R	Superior parietal	34	-58	50	4.88	.008
R	Precuneus	12	-62	50	4.84	.009
R	Superior frontal	22	0	46	5.21	.002
R	Anterior cingulate	14	8	44	4.76	.013
R	Inferior frontal	48	14	20	5.16	.002
R	Middle frontal	42	2	40	4.45	.044
L	Middle frontal	-40	50	-2	4.82	.010
R	Middle frontal	40	36	30	4.81	.010
R	Insula	32	18	0	4.72	.015
<b>b) Contingency x item type interaction</b>						
<b>(incongruent in MC set vs. congruent in MI set) – (incongruent in MI set vs. congruent in MC set)</b>						
Nihil						

L = left; R = right; x, y, z: coordinates (mm) in the stereotactic space defined by the Montreal Neurological Institute (MNI). These analyses were conducted with a  $p$  value < .05 FWE corrected.

Figure 1.

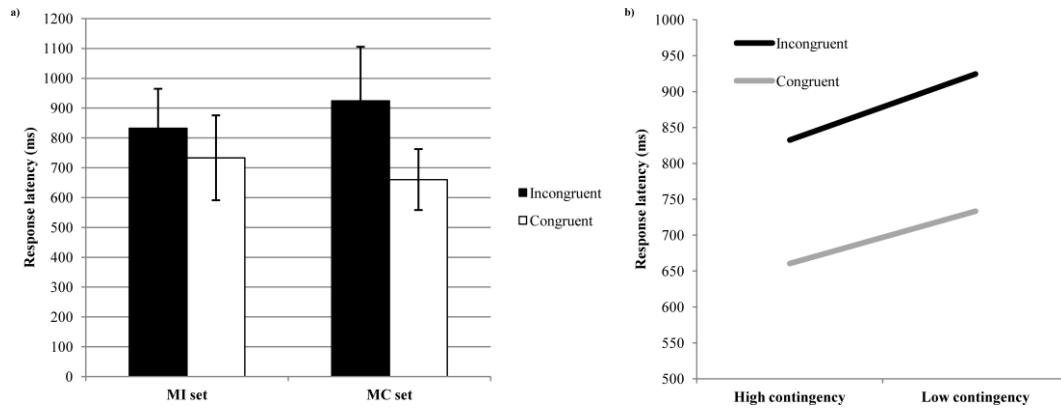


Figure 2

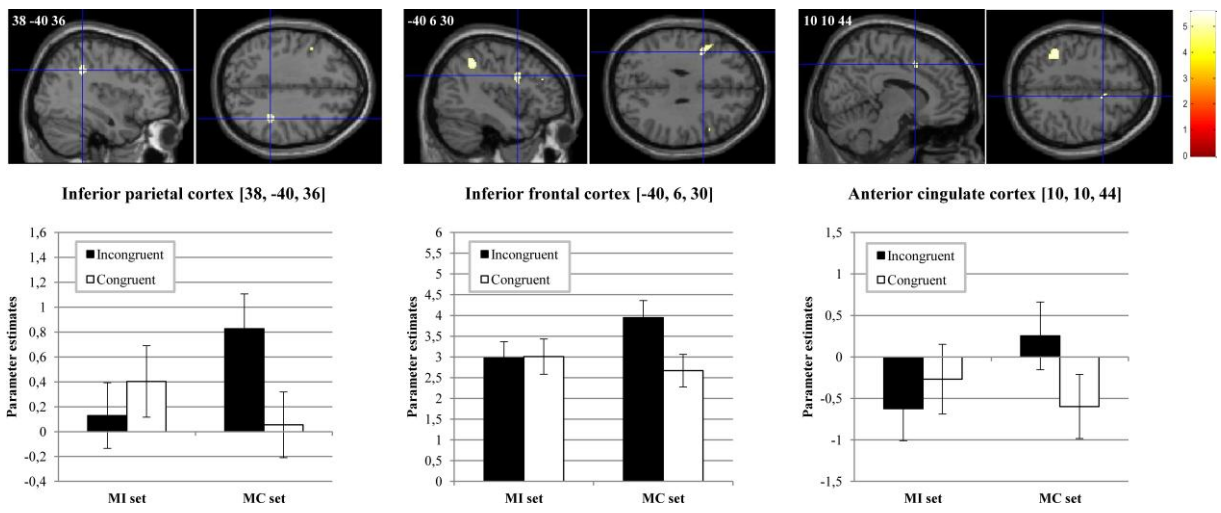


Figure 3



