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Title: Cognitive control during a spatial Stroop task: comparing conflict monitoring and prediction of response-outcome theories

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Highlights:

- We studied cognitive control as manifest in sequence effects in a conflict task.
- Incongruency in trial *n*-1 impacts trial *n* even when the task and stimuli change.
- Hypotheses derived from Conflict Monitoring Theory (CMT) were mainly countered.
- Hypotheses derived from Prediction of Response Outcome (PRO) theory were verified.
- Bottom-up and complex top-down processes arguably contribute to sequence effects.

Abstract

Cognitive control allows information processing and behaviour to vary adaptively from moment to moment depending on current goals. Two of the most prominent theories that have been proposed to account for the processing of cognitive control are the Conflict Monitoring Theory (CMT) and the Prediction of Response-Outcome Theory (PRO). According to both theories, the implementation of cognitive control during a trial in a conflict task reflects processing events that occurred in the preceding trial. Both CMT and PRO advocate that the detection of conflict situations leads to the recruitment of cognitive control, but they differ regarding the processing underpinnings of cognitive control during conflict resolution. CMT proposes that conflict between alternative responses is resolved by enhancing the task's relevant dimension, reducing interference from the task's irrelevant dimension(s). This control setup promotes conflict adaptation in the subsequent trial. PRO proposes that conflict is resolved by means of a cost-effectiveness analysis that identifies and suppresses action plans linked to the less appropriate responses, facilitating conflict resolution in the subsequent trial. To adjudicate between these alternatives, we manipulated contingencies pertaining to two-trial sequences (*n*-

1; *n*), namely, the congruency between task relevant/irrelevant dimensions in trial *n*-1 and response repetition in trial *n*. A spatial Stroop task was used, in which task-relevant and irrelevant information were integrated within the same stimulus. In this task, participants were required to attend to the direction of an arrow while ignoring its position. The arrow's direction and position could be congruent (C) or incongruent (IC). In one experiment, trials in which the participant was required to respond according to the position of a circle (PO; position only trials), occupying the sequential position *n*, were the focus of the analyses. Three experiments were conducted manipulating the trials' sequence structure. In Experiment 1, we studied a low control/low conflict condition (cC trials), and two high control/low conflict conditions (icC with and without response repetition). In Experiment 2, we studied two low control/no conflict conditions (cPO with and without response repetition) and two high control/no conflict conditions (icPO with and without response repetition). In Experiment 3, we studied a high control/high conflict condition (icIC) and two low control/high conflict conditions (cIC with and without response repetition). Overall, our findings are in agreement with previous studies in which both bottom-up processing, linked to response and stimulus position repetition, and top-down processing, linked to cognitive control, were shown to contribute to sequence effects in conflict tasks. Specifically, our observations mainly support PRO's account of conflict resolution, in which the intervention of top-down processing is substantially more complex than in CMT's account.

Keywords (max. 6): Cognitive control; Conflict monitoring; Prediction of Response-Outcome; Conflict resolution; Spatial Stroop; Sequence effects.

Classification codes (PsycINFO): 2100 General Psychology; 2300 Human Experimental Psychology; 2340 Cognitive Processes; 2346 Attention.

1. Introduction

Our current experience is influenced by prior experience at both large and surprisingly small time scales. Priming is an experimental effect that appropriately illustrates this latter type of influence. It reflects a "preparation" of

the cognitive system to process the target that makes use of primes' attributes and of their mapping onto the responses available within the task. Priming effects and their variation as a function of the prime/target relations are valuable means to investigate the nature of the processes that underpin such small time-scale "preparations". In conflict-tasks, such as the Stroop task (Stroop, 1935), priming effects allow us to probe the functioning of the cognitive control system, which is mobilized to manage and resolve conflict. With respect to such tasks, it is still a matter of debate how cognitive control is implemented. The Conflict Monitoring Theory (CMT; Botvinick, Cohen, & Carter, 2004) and the Prediction of Response-Outcome Theory (PRO; Alexander & Brown, 2011) provide particularly insightful, yet different, accounts regarding the processing of cognitive control in the management of conflict, in which the anterior cingulate cortex (ACC) seems to be involved. The CMT advocates that conflict between alternative responses is resolved by focusing on the task's relevant dimension and thus reducing interference from the task's irrelevant dimension(s). This results in conflict adaptation in the subsequent trial. According to the PRO, conflict between alternative responses is resolved after a cost-effectiveness analysis that identifies and eventually leads to the suppression of the incorrect action plan(s), leaving only the correct action plan(s) available for execution. According to both theories, sequence effects in conflict tasks reflect the implementation of cognitive control. Although the conflict monitoring function, advocated by the CMT, and the response-outcome prediction function, advocated by the PRO, are not necessarily mutually exclusive (for a unitary ACC function proposal, see Botvinick, 2007), the two theories offer distinct accounts regarding conflict resolution, a key feature of cognitive control implementation in conflict tasks.

1.1. Conflict Monitoring Theory (CMT)

Human neuroimaging studies with conflict tasks, such as the Stroop task (Stroop, 1935), the Eriksen flanker task (Eriksen & Eriksen, 1974) and the Simon task (Simon & Rudell, 1967), have found increased activation in the ACC when participants needed to suppress frequent responses, when they had to select one from a number of potentially correct responses, and when they

committed errors (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns, 2006; Larson, Kaufman, & Perlstein, 2009; Liotti, Woldorff, Perez, & Mayberg, 2000; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Based on the idea that this increased activation indexes the detection of conflict, Botvinick, Braver, Barch, Carter, and Cohen (2001) proposed the CMT. According to this theory, a conflict monitoring system is automatically activated in trials in which response conflict is present. Response Conflict is defined by Botvinick et al. (2001) as the simultaneous activation of mutually inhibiting responses. The role of the conflict monitoring system is to signal the need for increased cognitive control, relaying this request to the prefrontal regions that instantiate the required processes. The prefrontal control system then resolves the conflict by biasing attentional focus towards the task's relevant stimulus information and reducing the interference of the task's irrelevant stimulus information (Egner & Hirsch, 2005). Botvinick et al. (2001) propose that lateral inhibition plays an important role in conflict resolution. In their computational models, lateral inhibition is present within both the response layer and the stimulus layer. Specifically, the response representation, enhanced by increased upcoming activation from stimulus' relevant information, actively contributes to the suppression of the competing response via their mutually inhibitory connections. In a similar manner, the stimulus' feature unit, enhanced by an attentional bias, further magnifies its saliency as a result of the inhibitory connections with the other units, reducing interference from irrelevant information.

1.2.The Prediction of Response-Outcome Theory (PRO)

Another stream of data suggests that the ACC is engaged in computing the expectable outcomes of a response before its occurrence, yielding information valuable in guiding response selection when several options are available (for a review, see Yeung, 2013). Different functions have been attributed to ACC regarding its capacity to guide behaviour by response-outcome association: the detection of discrepancies between actual and expected outcomes (Holroyd & Coles, 2002); error likelihood prediction (Brown & Braver, 2005, 2007); the detection of unpredicted responses (Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003); the detection of volatility (Behrens, Woolrich, Walton, & Rushworth,

2007); and the capacity to learn from errors (Hester, Barre, Murphy, Silk, & Mattingley, 2008). To account for all these findings, the PRO was proposed (Alexander & Brown, 2010, 2011). The core processes in PRO involve mappings between existing action plans in a stimulus context and predictions of the responses and outcomes that are likely to result (Alexander & Brown, 2011). These action plans are abstract functions projecting the value of a given stimulus feature onto a response (e.g., if stimulus at position x, response at position x). PRO is to a large extent a learning theory and therefore has a primary focus on the process of learning the aforementioned mappings, as it unfolds in tasks in which the correct response is not instructed but must be learned by trial-and-error using feedback. However, PRO also describes the mechanisms that make use of those mappings when they were fully learned or directly defined by the task's instructions. Accordingly, PRO also models performance in tasks in which the required response is clearly defined by instructions such as conflict tasks in which participants must select the task-appropriate responses when competing alternatives are also present (Alexander & Brown, 2011; Yeung, 2013). It is the set of mechanisms that PRO proposes with respect to this type of task that is of interest in our present work. According to PRO, conflict effects are due to the prediction of multiple responses. Incongruent stimuli signal an overall prediction of responding to the distractor and, therefore, the presence of correct and incorrect action plans, which must be distinguished from each other (Alexander & Brown, 2011). To isolate the appropriate action plan, the ACC predicts the responses and outcomes that each plan should yield (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006). Action plans yielding predicted responses with an unacceptable cost (e.g., high error probability) are suppressed, leaving only the action plan yielding the least amount of effort or risk (Botvinick, 2007; Brown & Braver, 2007). The suppression process is instantiated by an "amend/veto" function (Alexander & Brown, 2010) associated with the response-outcome predictions. This settles response selection, leaving only the most appropriate action plan available.

1.3.Sequence Effects

The role of conflict in the recruitment of control has become apparent in studies of trial-by-trial adjustments of cognitive control. The terms "conflict adaptation", "*Gratton* effect", and "sequential trial effects" are frequently used to refer to these trial-by-trial adjustments (Egner, 2007; Gratton, Coles, & Donchin, 1992; Kerns et al., 2004). These sequence effects were first found in the Eriksen flanker task (Gratton et al., 1992). Usually, in this conflict task, the participant must respond to the direction of a central arrow, the target, while ignoring the direction of arrows appearing on the sides, the flankers. The flankers can be pointing to the same side as the target (i.e., C trial) or they can be pointing to the opposite side (i.e., IC trial). Two relevant sequence effects have been described with respect to the Eriksen flanker task and other conflict tasks: (i) a faster and more accurate response to an incongruent (IC) trial preceded by another IC trial (icIC) relative to the response to an IC trial preceded by a congruent (C) trial (cIC); (ii) a faster and more accurate response to a C trial preceded by another C trial (cC) relative to a C trial preceded by an IC trial (icC; Gratton et al., 1992; Sturmer, Leuthold, Soetens, Schroter, & Sommer, 2002; Ullsperger, Bylsma, & Botvinick, 2005). Sequence effects supposedly due to the management of conflict/incongruency are likely to reflect other variables associated with the trial sequence, namely, response repetition and/or repetition of the stimulus position. In particular, the accounts of cognitive control and conflict resolution we intend to confront, CMT and PRO, yield predictions pertaining to the deployment of cognitive control and its manifestations in sequence effects in conflict trials that reflect not only the trials' congruency but also whether or not trial *n* repeats the response or stimulus position that occurred in trial *n-1*. Namely, for CMT, lateral inhibition between conflicting motor response representations should translate into negative priming effects when a response inhibited in trial *n*-1 is the correct response in trial *n*. According to PRO, conflict resolution involves goal structures and action plans that are abstract and not immediately connected to specific motor response representations. Thus, response repetitions should mainly interact with aspects of the control goal structure assembled in trial *n*-1, as for instance the repeated recruitment in trial *n* of an action plan and specific predicted response that were activated in trial *n*-1. There are, additionally, some configurations of stimulus-response repetition that might affect trial sequences due to processes that have

no relevance for examining the CMT/PRO contrast and that would instead obscure the results bearing on that contrast. That would be the case of exact stimulus-response repetitions that occur in IC-IC and C-C sequences (benefiting processing in the second trial). In both Mayr, Awh, and Laurey (2003) and Nieuwenhuis et al. (2006), sequence effects were absent in a flanker task if sequences with exact stimulus-response repetitions were excluded and if only response repetitions in the absence of stimuli repetition (occurring in IC-C and C-IC sequences, increasing difficulty while processing the second trial) were considered in the analyses. Other studies found sequence effects in the flanker task when stimulus and/or response repetitions effects were controlled (Ullsperger et al., 2005; Verbruggen, Notebaert, Liefooghe, & Vandierendonck, 2006). Using other conflict tasks, studies that controlled for both exact and partial stimulus-response repetitions also identified sequence effects, namely with the Stroop and Simon tasks (Notebaert, Gevers, Verbruggen, & Liefooghe, 2006; Sturmer et al., 2002; Wuhr & Ansorge, 2005). Overall, these findings highlight the relevance for sequence effect studies of eliminating the effect of complete stimulus-response repetitions and incorporating into their design the distinctive features of the remaining repetition combinations, response repetition without stimulus repetition and complete response-stimulus mismatch.

In the experiments we conducted to probe these sequence effects, we omitted full stimulus-response repetitions. A spatial Stroop task was used. Although the sequence effects that interest us were first described with respect to the Eriksen flanker task, we considered that a task in which spatial position segregates irrelevant (flankers) and relevant information (target) information would not be the most appropriate ground to conduct a comparison between CMT and PRO accounts of cognitive control. This is because in an Eriksen flanker task conflict trial, a response according to flanker information is never a prevalent response and, therefore, is not a particularly strong competitor to the appropriate response. Additionally, the spatial segregation of relevant (central) and irrelevant information (left and right) probably facilitates the use of low-level attentional strategies that could effectively eliminate flanker interference. Taken together, these aspects of an Eriksen flanker task could contribute to results reflecting a fairly simple perceptual tuning effect or some visual attention biasing strategy that might not heavily rely on top-down control. Since we were interested in

probing the nature of such control mechanisms, we devised a task more likely to reflect their intervention. Namely, we conflated in a single stimulus irrelevant left/right position information with relevant direction information. This yielded the spatial Stroop task that we used in our experiments, necessarily requiring some degree of central processing to dissociate relevant and irrelevant information and creating strong competitors to the appropriate response in conflict trials, due to the presence of a Simon effect.

1.4. The spatial Stroop task and cognitive control

In a spatial Stroop task, direction-words or arrows may be used as stimuli. In the arrow-version of such tasks (Funes, Lupianez, & Milliken, 2007; Luo, Lupianez, Funes, & Fu, 2013; Luo & Proctor, 2013), participants are asked to respond to the left/right direction of an arrow regardless of its left/right position on a computer screen. As in the Simon task (Simon & Small, 1969), there is a tendency to respond with the hemibody matching the side of the stimulus presentation. This effect provides, in the context of a Stroop task, a prevalent response associated with the irrelevant stimulus' dimension that must somehow be suppressed in conflict trials. In the spatial Stroop task, both Stimulus-Stimulus (S-S) and Stimulus-Response (S-R) interference are present (Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005). Conflict in IC trials may therefore emerge at two distinct levels: S-S, pertaining to selectively attending one or the other information source present, and S-R, pertaining to the competing response mappings for each of the information sources. In congruent trials, S-S conflict may arise, but S-R conflict is absent since both information sources map onto the same response. Crucially, CMT and PRO theories differ in their account of conflict resolution. According to both the CMT and PRO theories, in IC trials, two incompatible responses are prepared: (i) the response according to the arrow's direction and (ii) the response according to the arrow's position. The presence of different response options is identified as impeding a successful trial, and the level of control is increased to overcome the situation. After this initial step, the CMT and PRO theories advocate different mechanisms to achieve conflict resolution. CMT proposes that increased control translates into an enhancement of the task-relevant dimension (i.e., direction), reducing

interference from the task-irrelevant dimension (i.e., position). This biased activation flowing between layers, from the stimulus onto the response layer, induces higher activation of the response linked to the arrow's direction. According to the computational model proposed by Botvinick et al. (2001), lateral inhibition magnifies the differential activation of units within the response layer (left/right responses) and within the stimulus features' layer (direction and position units). This interplay of biased between-layer activation and within-layer lateral inhibition eventually resolves conflict. PRO advocates that conflict in an IC trial comes from the existence of multiple response plans and corresponding expected responses. When an IC trial signals the expectation of responding to the task-irrelevant information, top-down control is recruited, establishing the goal of suppressing the action plan with the least favourable outcome. Assigning such an outcome requires activation of the task's criterion that identifies the action plan associated with a predicted incorrect response, which, in our spatial Stroop task, is the one yielding a response to the side where the arrow is located. This action plan is associated with an unacceptable cost (i.e., an erroneous response), and its execution must therefore be prevented. Crucially, the PRO advocates that cognitive control always acts by choosing the best cost-effectiveness process. The suppression of the incorrect action plan is the most cost-effective process, leaving only the task-appropriate action plan (e.g., responding to the side indicated by the arrow's direction) available for execution. It should also be noted that the response representations that are in use during conflict processing lie at different abstraction levels for the CMT and for the PRO. While for the CMT these representations are closer to the motor programs responsible for execution—as indicated by the mutual lateral inhibition connections between incompatible responses, upon which conflict detection relies—for the PRO, the relevant representations are notably more abstract (action plans and corresponding response-outcome predictions).

We present three experiments designed to contrast CMT and PRO predictions with respect to sequence effects in a spatial Stroop task, in which the congruency type of the first in a two-trial sequence was varied, as well as response/position repetition. Only trials without complete stimulus-response repetitions were used.

2. EXPERIMENT 1 – Sequence effects on congruent (C) trials

2.1.Purpose

In Experiment 1, we analysed the effect of the trial *n*-1 congruency type on an *n* C trial. Three different types of C trials were considered: cC trials without response repetition ($cC^{R\neq}$); icC trials with response repetition ($icC^{R=}$); and icC trials without response repetition ($icC^{R\neq}$).

We expected that the processing of both $icC^{R\neq}$ and $icC^{R=}$ trials would be impaired relative to $cC^{R\neq}$ trials. According to CMT, in *n*-1 IC trials, the biased activation of the relevant stimulus information (i.e., direction) leads to increased saliency of the direction response, with a corresponding decrease in the position response pathway. According to PRO, the goal of suppressing the action plan associated with an expected incorrect response that was established to obtain the best outcome in the *n*-1 IC trial should be primed in the *n* C trial, as should the criterion defining incorrectness (i.e., same-sided response-stimulus). In the *n* C trial, this setup initially results in inappropriate marking for suppression the correct response, since in a C trial, direction and position information lead to the same response.

For the comparison of the $icC^{R=}$ and $icC^{R\neq}$ trials, we expected, according to CMT, an impairment in $icC^{R\neq}$ trials due to lateral inhibition within the response layer. In the $icC^{R\neq}$ trials, direction and position are mapped onto the same response, but this response is the one that was suppressed due to lateral inhibition between the left-right responses in the *n*-1 IC trial. The response required in the *n* C trial is the one inhibited in the *n*-1 IC trial, leading to accrued impairment in the $icC^{R\neq}$ trials relative to the $icC^{R=}$ trials. PRO does not predict a differential impairment of $icC^{R\neq}$ and $icC^{R=}$ trials, given that in the IC trial, an action plan ("respond according to stimulus side") was suppressed and not a specific (left/right) representation of a motor response.

In addition to the C and IC trials included in the critical sequences described above, we included in non-critical sequences position-only (PO) trials (i.e., trials in which the participant has to respond according to the position of black circles that do not convey any direction information). PO trials were introduced in order to reduce the possibility of developing and automatizing

facilitating strategies (e.g., focusing attention on the head of the arrow and systematically suppressing information concerning its spatial position), since that could reduce the spatial Stroop effect (Lu & Proctor, 1995). In the PO condition, the stimulus position is the relevant dimension, thus preventing the participants from automatizing the blocking of position information. The proportion of PO trials was kept low (11 % of the total trials) in order to preserve the nature of the task. We expected to find a spatial Stroop effect (i.e., impairment of IC trial processing relative to C trial processing), to which the PO trials should have contributed. The inclusion of PO trials implied the presence of task-switching, as participants had to use the instruction to respond according to the stimulus on-screen positioning for PO trials and shift to the main instruction of responding to the arrows' direction when such a stimulus followed a PO (and vice-versa). To prevent a direct task-switching effect affecting the first trial (*n*-1) in a critical sequence, which could somehow affect RTs and the accuracy in the trial *n*, we controlled the type of trials *n*-2 (i.e., trials preceding *n*-1). PO trials never occurred immediately before trials *n*-1. PO trials were oddballs in Experiment 1 (11 %), and their rarity should therefore prevent the necessity of keeping the PO task instruction in working memory while performing the dominant task. The presence of PO trials probably amplified conflict in the IC trials due to the fact that position could not be systematically ignored throughout the task. However, this possible amplification, although it may have had some influence on the magnitude of the sequence effects under study, should not have affected their nature. Finally, the number and distance of PO trials appearing before critical sequences could not consistently differ between different conditions of the experiments, and a confounding variable could not therefore emerge.

2.2.Method

2.2.1. Participants

Forty undergraduate Psychology students at the University of Coimbra participated for course credit. All participants provided written informed consent

in accordance with institutional guidelines. Exclusion criteria comprised current or previous diagnosis of a psychiatric or neurologic disorder, psychoactive medication use, brain injury, and uncorrected visual impairment. Participants were screened for depressive symptoms with the Beck Depression Inventory II (Beck, Steer, & Brown, 1996), and a cut-off of 20 points (i.e., moderate depression symptoms) was used to determine exclusion. Due to the presence of moderate depressive symptoms, three participants were excluded from data analysis. As a result, data from thirty-seven young adults (32 female; 18 - 26 years old, M = 19.14, SD = 1.62; 11 - 17 years of formal education, M = 12.5, SD = 0.99) were analysed. All participants in this and subsequent experiments took part in only one of them.

2.2.2. Materials and Procedure

Participants were tested on a computer running E-prime software (Psychology Software Tools, Inc.; www.pstnet.com/products/e-prime/). They sat comfortably in front of a 17'' computer screen at a distance of approximately 100 cm in a dimly lit room. During the task, three white boxes were horizontally displayed on a navy blue screen (see Fig. 1): one was presented centrally and the other two were presented on each side of the central box, equidistant from the centre of the screen. The stimuli consisted of black arrows presented inside the lateral boxes. Participants were asked to maintain their fixation on the centre of the screen before the target was presented. They were instructed to make left/right button presses using two switches, one held in each hand, in response to the right/left direction of an arrow.

The sequence of events in each trial/sequence is shown in Fig. 1.

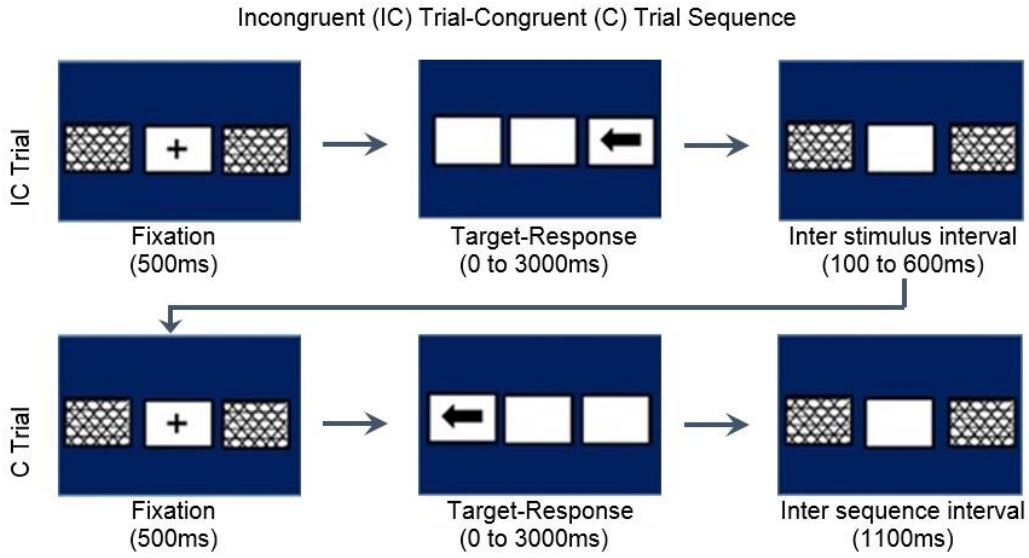

Fig. 1 - The sequence of events in each trial/sequence in the spatial Stroop task: an example of a sequence composed of an IC trial and a C trial.

At the beginning of each trial, the fixation point (a cross displayed inside the box located in the centre of the screen) and two lateral boxes filled with masks were presented for 500 ms. Then, the fixation point disappeared from the central white box and the target appeared in the right or left lateral boxes and remained on-screen until the participant responded, with a time limit of 3000 ms. Participants' responses triggered the offset of the stimulus display, which was followed by an inter-stimulus interval (ISI) that could vary between 100 and 600 ms. During ISI, masks were displayed in the lateral boxes and the central box remained blank. Mask presentation was used to overcome afterimage effect issues (Pilling, 2007). A second trial then began with the same structure of the first one, starting with a fixation cross, followed by the stimuli display. Stimulus offset was followed by a fixed inter-sequence interval of 1100 ms to prevent accumulated eye strain while remaining unnoticeable to participants, as confirmed during debriefing. As during ISI, in the inter-sequence interval, masks were displayed in the lateral boxes and the central box remained blank during the inter-sequence interval. The task comprised 664 trials that were presented in prearranged sequences of which participants were unaware, the succession of different trial types being perceived as random. The focus of our experiment was the following critical sequences: $icC^{R\neq}$, $icC^{R=}$, and $cC^{R\neq}$ (see Table A in the Appendix A for a visual representation). Full stimulus-response repetitions (e.g.,

a C trial requiring the right response preceded by other C trials that required the same response) were not included. To obtain an equal proportion of C and IC trials, filler sequences were created. These non-critical sequences included icIC trials and cIC trials, as well as other sequence types combined with PO trials.

The proportion of C and IC trials was 44.58 % each, and the proportion of PO trials was 10.84 %. The proportion of response types was balanced in our task, with 50 % requiring a left response and 50 % requiring a right response. The experiment comprised three short breaks, dividing the overall duration of each participation into four parts comprising an equal number of trials and keeping the proportions of C, IC, and PO trials stable in each part (166 trials, of which 72 were critical trials; overall: 74 C trials, 74 IC trials and 18 PO trials). The overall duration of the time-on-task was 20 mins. Before engaging in the main task, participants performed 28 practice trials and were instructed to respond as quickly as possible while trying to avoid errors.

2.2.3. Data analysis

Sequence effects were analysed by comparing three conditions ($cC^{R\neq}$, $icC^{R\neq}$ and $icC^{R=}$). Pairwise comparisons were always performed using the Bonferroni correction. Potential confounding factors while examining sequence effects may emerge as a consequence of including error and post-error trials (Egner & Hirsch, 2005). Error trials are frequently associated with faster reaction times (RTs; Ridderinkhof, 2002), while post-error trials are associated with consistent RT slowing (Rabbitt, 1966). Thus, we excluded error and post-error trials from our analyses. This procedure excluded 9 % of the responses. One percent of the responses were excluded in the $cC^{R\neq}$ condition, while 13 % were excluded in the $icC^{R\neq}$ and the $icC^{R=}$ conditions. Anticipations (RTs < 100 ms and RTs 3SD lower than the participant's mean for a given experimental condition) and lapses of attention (RTs more than 3SD higher than the participant's experimental condition mean) were also excluded. This cut-off procedure excluded < 2 % of the remaining responses with similar exclusion rates for the different conditions (±1.8 % in each condition). To assess sequence effects, we performed two separate one-way repeated-measures analyses of

variance (ANOVAs), one pertaining to correct responses' RTs and the other to accuracy rates.

In addition to the sequence effect analyses, differences in the processing of C and IC trials were analysed in order to assess the spatial Stroop effect. Two paired-samples t-tests were performed for correct responses' RTs and for accuracy. Trial *n*-1 responses (i.e., first trial responses) in C-C and IC-C critical sequences were used in these analyses.

We used an alpha level of .05 for all statistical tests.

2.3.Results

The C and IC trials in Experiment 1 were compared before the analysis of the critical sequence effects. We found slower RTs for IC trials (M= 501 ms, SD = 81.2 ms) relative to C trials (M = 435 ms, SD = 77.2 ms), $t(36) = 11.726$, $p < 0.001$, and lower accuracy rates for IC trials (M = 88 %, SD = 8.4 %) relative to C trials (M = 99 %, SD = 1.3 %), $t(36) = -7.926$, $p < 0.001$. Thus, a reliable spatial Stroop effect was found relative to both RTs and accuracy. The association between Stroop interference and possible sequence effects is therefore duly grounded. The remaining analyses concern the examination of such sequence effects.

RTs and accuracy rates for each sequence condition are shown in Fig. 2.

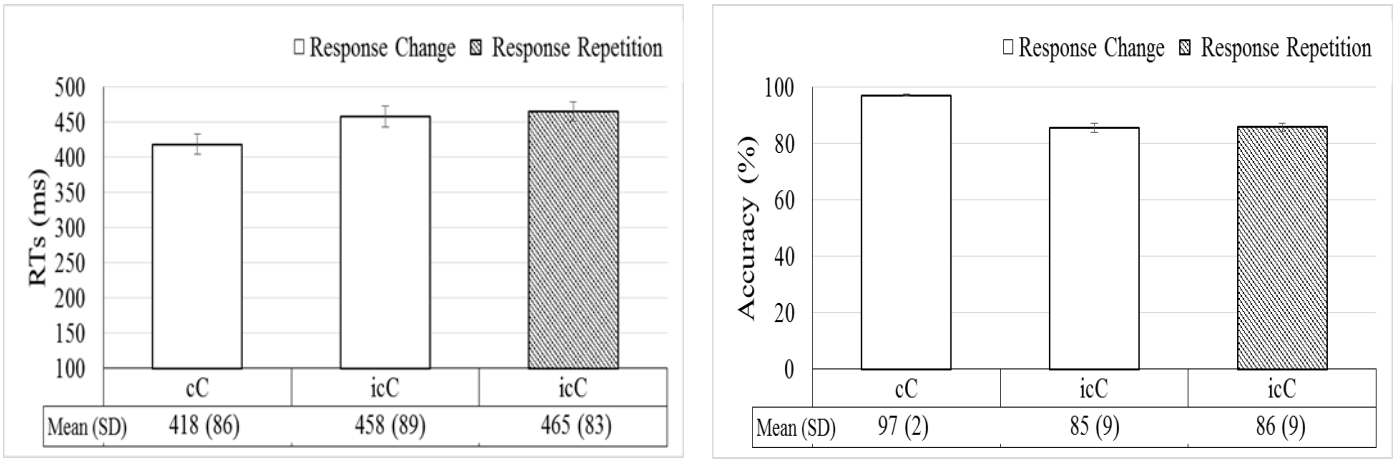

Fig. 2 - RTs and accuracy for the critical conditions: cC trials with response change (cC white bar); icC trials with response change (icC white bar); icC trials with response repetition (icC pattern bar). Error bars represent the standard errors (SE).

A repeated measures ANOVA determined that RTs differed significantly between the sequence conditions [$F(2, 72) = 47.061$, $p < 0.001$, $\eta^2_p = .567$]. Pairwise comparisons revealed that the responses to the $cC^{R\neq}$ trials (M = 418 ms, SD = 85.9 ms) were 39 ms faster relative to the $icC^{R\neq}$ trials (M = 458 ms, SD = 89 ms) [$F(1, 36) = 60.918$, $p < 0.001$, $\eta^2_p = 0.629$] and 46 ms faster relative to the $icC^{R=}$ trials (M = 465 ms, SD = 83.4 ms) [$F(1, 36) = 95.196$, $p < 0.001$, $\eta^2_p = 0.726$]. The $icC^{R\neq}$ and $icC^{R=}$ trials' RTs did not differ significantly [$F(1, 36) = 1.648$, $p = 0.207$, $\eta^2_p = 0.044$]. A repeated measures ANOVA determined that accuracy differed significantly between the sequence conditions [$F(2, 72) = 48.471$, $p < 0.001$, $\eta^2_p = .574$]. Pairwise comparisons revealed that responses to the $cC^{R\neq}$ trials were 12 % more accurate (M = 97.1 %, SD = 1.8 %) than those to the $icC^{R\neq}$ trials (M = 85.4 %, SD = 9.2 %) [$F(1, 36) = 60.865$, $p < 0.001$, $\eta^2_p = 0.628$] and 11 % more accurate than the responses to the $icC^{R=}$ trials (M = 85.8 %, SD = 8.9 %) [$F(1, 36) = 64.971$, $p < 0.001$, $\eta^2_p = 0.643$]. The difference in accuracy between the $icC^{R\neq}$ and $icC^{R=}$ trials was non-significant [$F(1, 36) < 1$, ns].

As predicted by both PRO and CMT, the $icC^{R\neq}$ and $icC^{R=}$ trials were impaired relative to the $cC^{R\neq}$ trials. No differences were found in the processing of the $icC^{R\neq}$ and $icC^{R=}$ trials. This result counters the CMT, from which we derived the prediction of an accrued impairment in $icC^{R\neq}$ trials due to lateral inhibition in the response layer. Accordingly, the results observed are better explained by the PRO, highlighting the role of the suppression of the incorrect action plan, defined at an abstract level in which representations of the specific values of stimulus attributes are not integrated.

3. **EXPERIMENT 2** – Sequence effects on position only (PO) trials

3.1.Purpose

The main purpose of Experiment 2 was to clarify some interpretation issues pertaining to the results of Experiment 1. In Experiment 1, we tested the

prediction derived from CMT that icC$^{R\neq}$ trials would be impaired relative to icC$^{R=}$ trials. This would be due to lateral inhibition in the response layer during the *n*-1 IC trial, affecting the response that should be produced in the following trial. In fact, we found no differences between the icC$^{R\neq}$ and icC$^{R=}$ trials. However, and still according to CMT, another effect of processing an *n*-1 IC trial would be the enhancement of direction information in the stimulus layer, establishing a bias that would still be present, to same extent, in the following trial. Therefore, one could hypothesize that this latter sequential effect would neutralise the first, rendering the absence of differences between icC$^{R\neq}$ and icC$^{R=}$ trials compatible with CMT's mechanisms.

To clarify this possibility, we replicated Experiment 1, substituting *n* PO trials for *n* C trials. In the PO trials, the participant had to respond according to the stimulus position and, crucially, there was no direction information present. Therefore, CMT no longer provided a mechanism that might neutralise the impairment in icC$^{R\neq}$ trials, due to residual inhibition of the correct response. The processing of *n* PO trials was analysed by contrasting four conditions: cPO trials with response repetition (cPO$^{R=}$); cPO trials without response repetition (cPO$^{R\neq}$); icPO trials with response repetition (icPO$^{R=}$); and icPO trials without response repetition (icPO$^{R\neq}$).

We expected that the processing of both icPO$^{R\neq}$ and icPO$^{R=}$ trials would be impaired relative to cPO$^{R\neq}$. According to the CMT, in the *n*-1 IC trials, the increased activation of the relevant stimulus information (i.e., direction) leads to a reduced activation of the irrelevant one (i.e., position). Even though PO trials do not contain direction information, it might still be conceivable that the position feature pertaining to a PO stimulus' representation would be hindered in its capacity to activate the corresponding correct response, due to lateral inhibition within the stimulus layer occurring in the previous IC arrow trial. According to the PRO, activation of the goal of suppressing an action plan associated with a predicted incorrect response would have been necessary to obtain the best outcome in the *n*-1 IC trial. This goal should therefore be primed in the *n* PO trial, as should the criterion defining incorrectness (i.e., same-sided response-stimulus). In the *n* PO trial, this setup would initially result in inappropriately selecting for suppression the correct action plan, since in PO trials, the action plan that would provide the correct response is associated with a

predicted response matching the criterion for defining incorrectness used in the previous IC trial.

For the icPO$^{R=}$ and icPO$^{R\neq}$ trial comparison, we expected, according to CMT, an impairment in icPO$^{R\neq}$ trials as an after-effect of the lateral inhibition within the response layer that occurs in the *n*-1 IC trial. The left/right response required in icPO$^{R\neq}$ trials should have been inhibited in the *n*-1 IC trial, leading to an accrued impairment in icPO$^{R\neq}$ trials relative to icPO$^{R=}$. No differences are predicted by PRO regarding the icPO$^{R\neq}$ and icPO$^{R=}$ contrast, since suppression in IC trials impacts abstract action plans ("respond according to stimulus side"), not specific (left/right) representations of motor responses.

A fourth condition, comprising cPO trials with response repetition (cPO$^{R=}$), which could not be included in Experiment 1 because it would feature full response-stimulus repetitions, was now considered in Experiment 2, since stimuli always vary across trials when using arrow-circle sequences.

As in the previous experiment, C, IC and PO trials were included in the task. The proportion of PO trials was higher (33.33 %) than in Experiment 1 in order to balance the trial types' proportion. We expected to find a spatial Stroop effect (i.e., impairment of IC trial processing relative to C trial processing), to which the PO trials should have contributed.

3.2.Method

The method in this experiment was the same as in Experiment 1, except for the information added bellow.

3.2.1. Participants

Forty participants took part in Experiment 2. Due to the presence of moderate depressive symptoms, five participants were excluded from the data analysis. Two more participants were excluded due the use of psychoactive medication. Another was excluded due to severe congenital auditory deficits. As a result, data from 32 young adults (31 female; 18 - 24 years old, *M* = 18.8, *SD* = 1.41; 12 - 17 years of formal education, *M* = 12.8, *SD* = 1.44) were analysed in this experiment.

3.2.2. Materials and Procedure

The main task was composed of 675 trials that were organized into sequences. There were four critical sequences: $cPO^{R=}$, $cPO^{R\neq}$, $icPO^{R\neq}$ and $icPO^{R=}$ (for a visual representation, see Table A from the Appendix A section). Non-critical sequences of trials, including sequences such as poPO, cIC and icC, were also presented in order to obtain equal proportions of PO, C and IC trials (33.33 % each). The experiment comprised two short breaks, dividing the overall duration of each participation into three parts comprising an equal number of trials and keeping the proportions of C, IC, and PO trials stable in each part (225 trials, of which 64 were critical trials; overall: 75 C trials, 75 IC trials and 75 PO trials). The overall duration of the time-on-task was 18 mins.

3.2.3. Data analysis

Sequence effects were analysed by comparing four conditions ($cPO^{R=}$, $cPO^{R\neq}$, $icPO^{R\neq}$ and $icPO^{R=}$). Pairwise comparisons were always performed using the Bonferroni correction. As in the previous experiment, error and post-error trials were excluded from the analysis. This excluded 7 % of the responses. The critical conditions ($icPO^{R\neq}$; $icPO^{R=}$; $cPO^{R\neq}$; and $cPO^{R=}$) were differently affected by this exclusion: 14 % of the responses were excluded in the $icPO^{R\neq}$ and $icPO^{R=}$ conditions; < 1 % were excluded in the $cPO^{R\neq}$ condition; and 2 % were excluded in the $cPO^{R=}$ condition. Anticipations and lapses of attention were also removed. This cut-off procedure excluded < 2 % of the total remaining responses with similar exclusion rates for the different conditions (±1.7 % in each condition). To assess sequence effects, we performed two separate two-way repeated measures ANOVAs with the factors *n*-1 trial's congruency (C vs IC) and *n*-1 and *n* trials' response match (response repetition vs response change), one pertaining to correct responses' RTs and the other to accuracy rates.

In addition to the sequence effect analyses, differences in the processing of the three trial types included in the critical sequences were analysed: C, IC and PO trials. We performed two separate repeated measures ANOVAs, one pertaining to correct responses' RTs and the other to accuracy rates. Trial *n*-1

responses in C-PO and IC-PO sequences without response repetition were used in these analyses as C and IC trials. Trial *n* responses (i.e., second trial responses) in C-PO sequences without response repetition were used in these analyses as PO trials. We selected the PO trials featured in $cPO^{R\neq}$ sequences, in which they are less affected by predictable sequence effects. $cPO^{R=}$ trials may exhibit partial match deleterious sequence effects (response repetition without stimulus repetition), while all icPO trials may be affected by interference with position processing. It should be noted that a task-shift effect may still negatively affect these $cPO^{R\neq}$ trials.

3.3.Results

To verify that our task induced a spatial Stroop effect in this experiment, we compared the *n*-1 C and IC trials in the critical sequences. Since PO trials were also part of these sequences, being the *n* trial therein, we also included them in an overall comparison. A repeated measures ANOVA was performed to compare RTs on the three trial types. Mauchly's test indicated that the assumption of sphericity had been violated [$\chi^2(2) = 14.211, p = 0.001$]; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (ε =.726). The three trial types differed significantly with respect to RTs [$F(1.452, 45.016) = 84.587$, $p < 0.001$, $\eta^2_p = 0.732$]. Follow-up pairwise comparisons revealed that responses to C trials (M = 381 ms, SD = 48.1 ms) were, on average, 86 ms faster than responses to IC trials (M = 467 ms, SD = 52.9 ms) [$F(1, 31) = 147.667$, $p < 0.001$, $\eta^2_p = 0.826$], while responses to PO trials (M = 390 ms, SD = 57.4 ms) were 77 ms faster than responses to IC trials [$F(1, 31) = 71.691$, $p < 0.001$, $\eta^2_p = 0.698$]. The difference between C and PO trials' RTs was non-significant [$F(1, 31) = 3.446$, $p = 0.073$, $\eta^2_p = 0.100$]. A second repeated measures ANOVA was performed to determine whether there were differences in accuracy between trial types. Mauchly's test indicated that the assumption of sphericity had been violated [$\chi^2(2) = 41.763$, $p < 0.001$]; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity ($\varepsilon = 0.571$). Accuracy rates differed significantly across trial types [$F(1.142, 35.399) = 27.563$, $p < 0.001$, $\eta^2_p = 0.471$]. Pairwise comparisons revealed that responses to C trials (M = 99 %, SD = 2.2 %) were

significantly more accurate than responses to IC trials, at 9 % in our sample (*M* = 90 %, *SD* = 9.7 %) [$F(1, 31) = 27.058$, $p < 0.001$, $\eta^2_p = 0.466$]. Responses to PO trials (*M* = 99 %, *SD* = 2 %) in our sample were 9 % more accurate than responses to IC trials [$F(1, 31) = 30.650$, $p < 0.001$, $\eta^2_p = 0.497$]. The difference between accuracy in C and PO trials was non-significant [$F(1, 31) < 1$, ns]. A significant spatial Stroop effect was therefore found in respect to both RTs and accuracy, as in Experiment 1. With respect to *n* PO trials, which were affected by no particular hindrance other than task-shift, the processing effort was comparable to that required in C trials, again supporting the analogy between Experiment 1 and Experiment 2, in which *n* C trials were used. The remaining analyses refer to the analysis of sequence effects that may result from or have an impact on this spatial Stroop interference.

RTs and accuracy for each sequence are shown in Fig. 3.

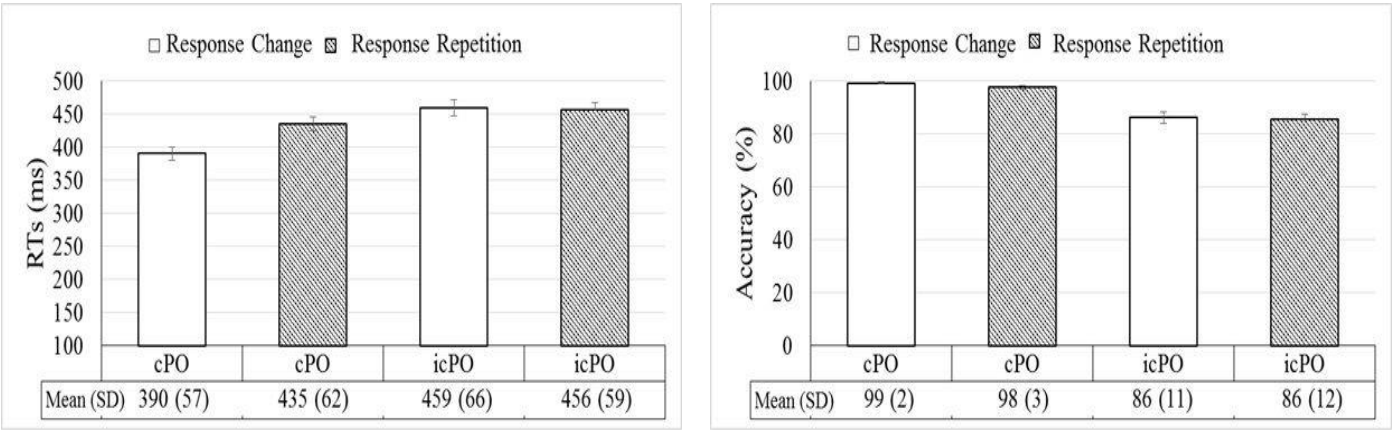

Fig. 3 - RTs and accuracy for the critical conditions: cPO trials with response change (cPO white bar); cPO trials with response repetition (cPO pattern bar); icPO trials with response change (icPO white bar); icPO trials with response repetition (icPO pattern bar). Error bars represent standard errors (SE).

A two-way repeated measures ANOVA was performed with the factors *n*-1 trial's congruency (C vs IC) and *n*-1 and *n* trials' response match (response repetition vs response change). There was a main effect of *n*-1 trial's congruency, with icPO trials (*M* = 458 ms, *SD* = 9.9 ms) being 45 ms slower that cPO trials (*M* = 413 ms, *SD* = 10.3 ms), [$F(1, 31) = 107.598$, $p < 0.001$, $\eta^2 p =$

0.776]. There was also a main effect of *n*-1 and *n* trials' response match, with response repetition trials (*M* = 446 ms, *SD* = 10.2 ms) being 21 ms slower than response change trials (*M* = 425 ms, *SD* = 10.5 ms), [$F(1, 31) = 11.265$, $p = 0.002$, $\eta^2 p = 0.267$]. There was a significant interaction between *n*-1 trial's congruency and response match, [$F(1, 31) = 34.005$, $p < 0.001$, $\eta^2 p = 0.523$]. Pairwise comparisons showed that this interaction was resolved by *n*-1 trial's congruency (C vs IC), with response repetition (*M* = 434 ms, *SD* = 61.6 ms) being slower than response change (*M* = 390 ms, *SD* = 57.4 ms) when the trial *n*-1 was congruent, [$F(1, 31) = 39.789$, $p < 0.001$, $\eta^2 p = 0.562$], and response repetition (*M* = 456 ms, *SD* = 58.9 ms) being as fast as the response change (*M* = 459 ms, *SD* = 65.7 ms) when the trial *n*-1 was incongruent, [$F(1, 31) < 1$, ns]. A two-way repeated measures ANOVA with the factors *n*-1 trial's congruency (C vs IC) and the *n*-1 and *n* trials' response match (response repetition vs response change) was also performed for accuracy. There was a significant main effect of *n*-1 trial's congruency, with responses to the icPO trials (*M* = 86 %, *SD* = 1.7 %) in our sample being 13 % less accurate than those to cPO trials (*M* = 98 %, *SD* = 0.4 %), [$F(1, 31) = 50.471$, $p < 0.001$, $\eta^2 p = 0.619$]. The main effect for the *n*-1 and *n* trials' response repetition was non-significant, with the performance in the response repetition trials (*M* = 91.5 %, *SD* = 1.1 %) being as accurate as in the response change trials (*M* = 92.6 %, *SD* = 1 %), [$F(1, 31) < 1$, ns]. The interaction between *n*-1 trial's congruency and response repetition was also non-significant, [$F(1, 31) < 1$, ns].

In Experiment 2, we clarified the results of Experiment 1. In Experiment 1, we tested the CMT prediction that $icC^{R\neq}$ trials would be impaired relative to $icC^{R=}$ trials, having not found differences between these two conditions. However, CMT's predicted effect with respect to response repetition might have been present, although obscured by the icC sequence effect within the stimulus layer. In fact, after processing an IC trial, the enhancement of direction information in the *n* C trial could have been powerful enough to cancel out the deleterious effect of having to produce a left/right response that had previously been inhibited. In Experiment 2, we replicated the sequence structures used in Experiment 1, but now using *n* PO trials, in which direction information is absent, instead of *n* C trials. As predicted by both PRO and CMT, the

icPO$^{R\neq}$ and icPO$^{R=}$ trials were impaired relative to the cPO$^{R\neq}$ trials, repeating the pattern observed in Experiment 1 (in which the icC$^{R\neq}$ and icC$^{R=}$ trials were impaired relative to the cC$^{R\neq}$ trials). We did not find any differences between icPO$^{R\neq}$ and icPO$^{R=}$trial processing, again replicating the pattern of the results of Experiment 1 (in which no differences were found between the icC$^{R\neq}$ and icC$^{R=}$ trials). Critically, with respect to the latter contrast, the null result in Experiment 2 cannot be explained by enhancement of direction information, since PO trials do not convey such information. Thus, this result counters the CMT prediction of an impairment in icPO$^{R\neq}$ trials relative to icPO$^{R=}$ due to lateral inhibition in the response layer. The results of Experiment 2, as those of Experiment 1, favour PRO in detriment of CMT.

The analysis of the full 2 x 2 design in Experiment 2 additionally allowed us to determine that *n*-1 incongruency hinders performance in a subsequent no-conflict trial irrespective of whether there is response repetition. Also, in the cPO vs icPO contrasts analysed, one of the trials in the critical sequences bore stimulus position repetition, while in the other, the stimulus position changed. The analysis of the full design showed that incongruency hinders performance in the subsequent trial irrespective of whether it is the cPO or the icPO trial that bears a repetition of the stimulus position. Experiment 2 further demonstrated that a sequential incongruency effect is present even when a different task and stimulus occur in the *n* trial.

4. **EXPERIMENT 3** – Sequence effects on incongruent (IC) trials

4.1.Purpose

In Experiment 3, we analysed the effect of *n*-1 trials on *n* IC trials. Three different types of IC trials were considered: icIC trials without response repetition (icIC$^{R\neq}$); cIC trials with response repetition (cIC$^{R=}$); and cIC trials without response repetition (cIC$^{R\neq}$).

From CMT, we derived the prediction that icIC$^{R\neq}$ trials would be facilitated relative to both cIC$^{R=}$ and cIC$^{R\neq}$ trials. The bias set-up by the attentional units over the features represented within the stimulus layer in the *n*-1 IC trial, enhancing the arrow's direction information in detriment of its position, should

still be present in the *n* IC trial, facilitating processing. According to the PRO, processing of $icIC^{R\neq}$ trials would be facilitated relative to $cIC^{R=}$ trials' processing. In the *n*-1 IC trial, the goal of suppressing the action plan associated with a predicted incorrect response was activated, as well as the criterion defining incorrectness (i.e., same-sided response-stimulus), in order to obtain the best outcome in that trial. The suppression goal and incorrectness criterion would then be primed in the *n* IC trial, facilitating the identification and suppression of the incorrect action plan in comparison to the same processes in a $cIC^{R=}$ trial. In $cIC^{R\neq}$, however, a specific facilitation effect would emerge according to PRO, the reason of which we detail below. Since there is no principled manner to derive from PRO a prediction about the relative strength of the $icIC^{R\neq}$ and $cIC^{R\neq}$ facilitation effects, we only predict the facilitation of $icIC^{R\neq}$ trials in relation to $cIC^{R=}$ trials.

We further derived from PRO the prediction that performance in $cIC^{R\neq}$ trials, in which the stimulus is presented in the same position in both trials (see Table A in the Appendix A), would be facilitated relative to performance in $cIC^{R=}$ trials. In the *n*-1 C trial, the action plans anchored on the arrow's spatial position and on its direction are both actively processed in order to compute the corresponding response-outcome predictions. Since there is no direction and position information match, the predicted response is the same for both plans, and there is therefore no activation of the goal of identifying and suppressing the plan that should yield an incorrect response. Accordingly, in the following trial, there would be remaining activation for the plan that computes a response on the basis of stimulus position and for its instantiation to a specific spatial position, corresponding to its predicted response. Since the trial *n* is an IC trial, the goal of suppressing the action plan with a predicted incorrect response would emerge. The action plan to which the suppression goal should apply projects onto the exact same predicted response as in the previous trial, i.e., to a representation that is primed. Therefore, the criterion defining incorrectness would benefit from this priming and deliver the "incorrect" outcome prediction more promptly than in a $cIC^{R=}$ trial, in which no such priming could occur. We did not derive from CMT a specific pattern of differences regarding the comparison between the $cIC^{R\neq}$ and $cIC^{R=}$ trials. In the *n*-1 C trial position and direction, information would project onto the same response representation within the response layer.

In this circumstance, no conflict would be detected and no attentional bias in favour of direction information would be established. We might speculate that even in the absence of conflict there would be strong lateral inhibition affecting the response not to be affected in a C trial. This would lead to predicting a pattern of differences between $icIC^{R\neq}$ and $cIC^{R=}$ trials opposite to that predicted by PRO. However, CMT does not elaborate upon the dynamics of excitatory and inhibitory processes in the absence of conflict.

As in Experiment 1, in addition to the C and IC trials included in critical sequences, we included PO trials in non-critical sequences in order to reduce the possibility of developing and automatizing facilitating strategies that could reduce the spatial Stroop effect. The proportion of PO trials was kept low (11 % of the total trials) in order to preserve the nature of the task.

4.2.Method

The method in this experiment was the same as in Experiment 1, except for the information added below.

4.2.1. Participants

Forty participants participated in Experiment 3. Due to the presence of moderate depressive symptoms, four participants were excluded from the data analysis. Accordingly, data from 36 young adults (31 female; 18 - 27 years old, *M* = 19.5, *SD* = 2.01; 9 - 17 years of formal education, *M* = 12.6, *SD* = 1.40) were analysed.

4.2.2. Materials and Procedure

The main task was composed of 648 trials, including equal proportions of C and IC trials (44.4 % each) and a low proportion of PO trials (11.1 %). There were three critical sequences: $cIC^{R=}$, $cIC^{R\neq}$, and $icIC^{R\neq}$ (see Table A in the Appendix A). As in Experiment 1, PO trials never occurred immediately before trials *n*-1 in order to minimize a possible task-switching effect directly impinging on critical sequences. The experiment comprised three short breaks, dividing the overall duration of each participation into four parts comprising an

equal number of trials and maintaining the proportions of C, IC, and PO trials stable in each part (162 trials, of which 72 were critical trials; overall: 72 C trials, 72 IC trials and 18 PO trials). The overall duration of the time-on-task was 20 mins.

4.2.3. Data analysis

Sequence effects were analysed by comparing three conditions (icIC$^{R\neq}$, cIC$^{R\neq}$ and cIC$^{R=}$). Pairwise comparisons were performed always using the Bonferroni correction. As in previous experiments, error and post-error trials were excluded from the analysis. This excluded 21 % of the responses in the critical sequences. In the cIC$^{R\neq}$ condition, 14 % of the responses were excluded, in the cIC$^{R=}$ condition 26 % and in the icIC$^{R\neq}$ condition 21 %. Anticipations and lapses of attention were also removed. This procedure excluded < 2 % of the total remaining responses, with similar exclusion rates for the different conditions (±1.6 % in each condition). To assess sequence effects, we performed two separate one-way repeated-measures analyses of variance (ANOVAs), one pertaining to correct responses' RTs and the other to accuracy rates.

In addition to the sequence effects analyses, we analysed performance differences between C and IC trials in order to assess the spatial Stroop effect. Two paired-samples t-tests were performed, one pertaining to RTs for correct responses another for accuracy data. Responses to trials *n*-1 in C-IC and IC-IC critical sequences were used in these analyses.

4.3.Results

Performance in C and IC trials was compared before the analysis of the critical sequence effects. We found slower RTs for IC trials (M = 461 ms, SD = 83.6 ms) relative to C trials (M = 401 ms, SD = 89.3 ms), $t(35) = -11.101$, $p < 0.001$, and smaller accuracy rates for IC trials (M = 84 %, SD = 13.3 %) relative to C trials (M = 99 %, SD = 1.5 %), $t(35) = -7.035$, $p < 0.001$. Thus, a reliable spatial Stroop effect was found for both RTs and accuracy. The remaining analyses pertain to the examination of sequence effects that may result from or impact this spatial Stroop interference.

The RTs and the accuracy for each sequence condition are shown in Fig. 4.

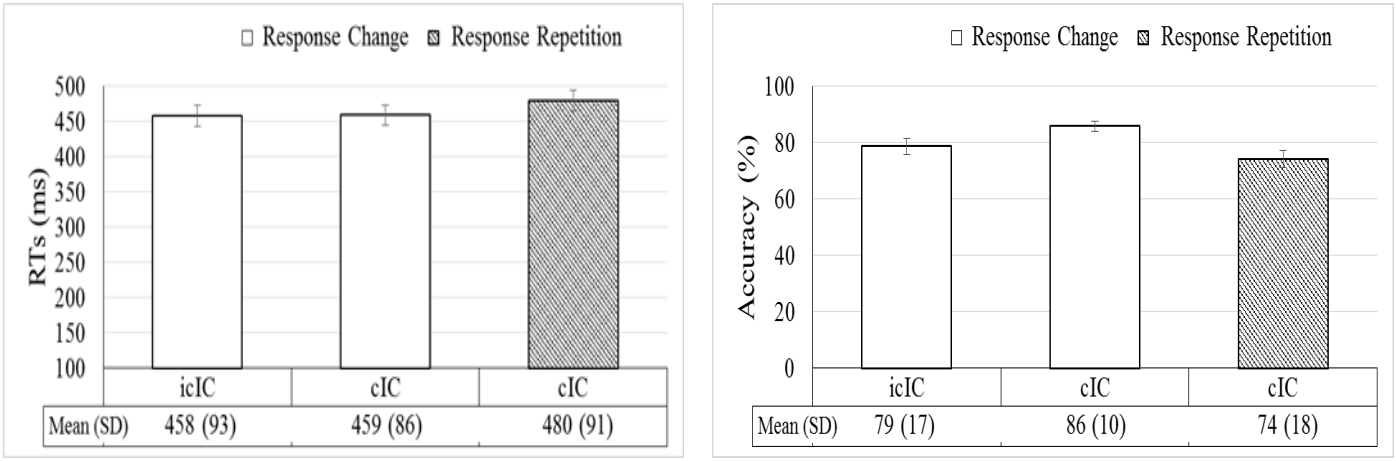

Fig. 4 - RTs and accuracy for the critical conditions: icIC trials with response change (icIC white bar); cIC trials with response change (cIC white bar); cIC trials with response repetition (cIC pattern bar). Error bars represent standard errors (SE).

A repeated measures ANOVA determined that RTs differed significantly among the three sequence conditions [$F(2, 70) = 8.164$, $p = 0.001$, $\eta^2_p = 0.189$]. Pairwise comparisons revealed that RTs in $icIC^{R\neq}$ trials (M = 458 ms, SD = 92.7 ms) and $cIC^{R=}$ trials (M = 480 ms, SD = 91.2 ms) were significantly different [$F(1, 35) = 14.228$, $p = 0.002$, $\eta^2_p = 0.290$], being 22 ms faster for $icIC^{R\neq}$ trials. $icIC^{R\neq}$ trials' RTs were as fast as in the $cIC^{R\neq}$ trials' RTs (M = 459 ms, SD = 85.6 ms) [$F(1, 35) < 1$, ns]. Responses to $cIC^{R\neq}$ trials were significantly faster than responses to $cIC^{R=}$ trials [$F(1, 35) = 10.336$, $p = 0.008$, $\eta^2_p = 0.228$], by 21 ms. A repeated measures ANOVA determined that the accuracy differed significantly among the three sequence conditions [$F(2, 70) = 26.588$, $p < 0.001$, $\eta^2_p = 0.432$]. Pairwise comparisons revealed that participants were significantly less accurate, by 7 %, in $icIC^{R\neq}$ trials (M = 79 %, SD = 17.1 %) relative to $cIC^{R\neq}$ trials (M = 86 %, SD = 10.4 %) [$F(1, 35) = 21.030$, $p < 0.001$, $\eta^2_p = 0.375$]. Another significant difference emerged for the comparison between the $icIC^{R\neq}$ and $cIC^{R=}$ trials (M = 74 %, SD = 17.8 %), now with participants being 4 % more accurate in $icIC^{R\neq}$ trials [$F(1, 35) = 10.213$, $p = 0.009$, $\eta^2_p = 0.226$]. In $cIC^{R\neq}$ trials, the accuracy was significantly better than in $cIC^{R=}$ trials [$F(1, 35) = 40.041$, $p < 0.001$, $\eta^2_p = 0.534$], by 12 %.

The results fully support the PRO and do not support the CMT. The $icIC^{R\neq}$ trial processing was facilitated only relative to the $cIC^{R=}$ trial processing. In the $cIC^{R\neq}$ trials, there was a facilitation effect that PRO would attribute to a faster identification and suppression of an action plan associated with a predicted incorrect response. The computation of its undesirable outcome involved a specific predicted response that was primed in the n IC trial. This should have occurred because the same predicted response was generated for the same action plan in the *n*-1 C trial. As a result, responses to $cIC^{R\neq}$ trials were as fast as those to $icIC^{R\neq}$ trials.

5. Discussion

The main purpose of our study was to contrast predictions derived from CMT and PRO theory with respect to conflict adaptation effects in a spatial Stroop task in order to establish which of these theories best accounts for the processing of cognitive control in such a paradigm. In this task, relevant and irrelevant task-information are integrated within the same stimulus, and a prevalent response is triggered by irrelevant information. The intervention of cognitive control processes should therefore be amply reflected by performance in such a task.

Concerning our main goal, we analysed different manipulations of congruency type patterns and response repetition/stimulus position repetition in sequences of two trials within the task. These manipulations were designed to highlight contrasts between CMT and PRO in their accounts of the processing underpinnings of cognitive control. Overall, the results obtained in this set of experiments seem to be better explained by the PRO than by the CMT (see Table 1).

Table 1 - Summary of the results obtained in the three experiments concerning to the comparisons between critical sequences in each experiment. There were six comparisons in each experiment, three for RTs and three for accuracy. A plus (+) sign is used when the results were in agreement with PRO or CMT predictions; a minus (—) sign is used to mark prediction/result disagreement.

Experiment/Critical Comparisons		Comparison of Predictions and Results			
		RTs		Accuracy	
		PRO	CMT	PRO	CMT
Experiment 1	$cC^{R\neq}$ vs $icC^{R\neq}$	+	+	+	+
	$cC^{R\neq}$ vs $icC^{R=}$	+	+	+	+
	$icC^{R\neq}$ vs $icC^{R=}$	+	—	+	—
Experiment 2	$cPO^{R\neq}$ vs $icPO^{R\neq}$	+	+	+	+
	$cPO^{R\neq}$ vs $icPO^{R=}$	+	+	+	+
	$icPO^{R\neq}$ vs $icPO^{R=}$	+	—	+	—
Experiment 3	$icIC^{R\neq}$ vs $cIC^{R\neq}$	+	—	—	—
	$icIC^{R\neq}$ vs $cIC^{R=}$	+	+	+	+
	$cIC^{R\neq}$ vs $cIC^{R=}$	+	*	+	*

*As stated in the purpose section of Experiment 3: We did not derive from CMT a specific pattern of differences regarding the comparison between $cIC^{R\neq}$ and $cIC^{R=}$ trials.

In Experiment 3, we found that performance in $icIC^{R\neq}$ trials was facilitated relative to $cIC^{R=}$ trials but not relative to $cIC^{R\neq}$ trials. This was only predicted by the PRO. According to this theory, in $icIC^{R\neq}$ trials, the goal of supressing the action plan is likely to yield an incorrect response, and the criterion identifying incorrectness that was activated in the *n*-1 IC trial is primed in the *n* IC trial. This results in a facilitated identification and suppression of the action plan, which is expected to yield an incorrect response in the second trial. However, a facilitation effect also occurred in the $cIC^{R\neq}$ trials, leading to a similar processing effort relative to the $icIC^{R\neq}$ trials. In $cIC^{R\neq}$ trials, the stimulus is presented in the same position as the stimulus presented in the *n*-1 C trial. In the *n*-1 C trial, both the direction-based and the position-based action plans were processed in order to compute the respective predicted response and outcome. Since the predicted response is the same for both plans, there is no activation of the goal of identifying and suppressing the plan that should yield an incorrect response. The position-based action plan and its predicted response are therefore primed in the subsequent trial. Accordingly, in an *n* IC trial repeating the stimulus position of the previous trial, when the suppression goal and incorrectness criterion are activated, there is already an active representation of the specific predicted

response for the position-based action plan. The process of matching that representation to the incorrectness criterion and the suppression of the corresponding plan will therefore be facilitated. According to CMT, $icIC^{R\neq}$ trials should have been facilitated relative to cIC trials, regardless of the response/position repetition in the C-IC sequences. CMT predictions were also countered by the pattern of data observed in Experiments 1 and 2. The similar processing effort of the $icC^{R\neq}$ and $icC^{R=}$ trials observed in Experiment 1 and of the $icPO^{R\neq}$ and $icPO^{R=}$ trials in Experiment 2 is mainly in accordance with PRO, countering CMT predictions. If lateral inhibition between incompatible responses played a significant role in conflict resolution, we should have found an impairment in $icC^{R\neq}$ and $icPO^{R\neq}$ trial processing relative to $icC^{R=}$ and $icPO^{R=}$ trial processing, respectively. Arguably, conflict resolution involves more-abstract representations, such as the action plans and expected response-outcomes that are advocated by PRO. These representations are quite far removed from representations of motor responses and do not involve mutually inhibitory connections.

The analysis of the full congruency type (2) x response repetition (2) design in Experiment 2 further helped resolve a possible confounding factor in Experiment 1. In fact, $icC^{R\neq}$ relative to $cC^{R\neq}$ differed both in *n*-1 congruency type and in position repetition ($cC^{R\neq}$ trials on opposite sides of the screen), while $icC^{R=}$ and $cC^{R\neq}$ differed both in *n*-1 congruency type and in response repetition (the $cC^{R\neq}$ trials bearing different positions). In Experiment 2, the use of different stimuli in the *n*-1 and *n* trials allowed us to include, in addition to a $cPO^{R\neq}$ condition corresponding to $cC^{R\neq}$ in Experiment 1, a $cPO^{R=}$ condition, without the problematic full stimulus-response repetition that would have occurred in $cC^{R=}$. This new condition creates a contrast with each icPO condition that is complementary, with respect to position repetition and response repetition, to that created by $cPO^{R\neq}$. Our results enable us to establish that *n*-1 incongruency hinders performance in the following trial, irrespective of whether there is response repetition and irrespective of which *n*-1 congruency type in a cPO vs icPO contrast bears a change or repetition in stimulus-position. This conclusion is based on the main effects found for *n*-1 congruency type in both RT and accuracy analyses, taken together with the fact that the significant interaction found in the RT analysis was not resolved by *n*-1 congruency type, with icPO

trials being hindered relative to cPO whether there was response repetition (with icPO bearing position repetition and cPO position change) or response change (with icPO bearing position change and cPO position repetition). Experiment 2 also added to Experiment 1 by showing that this sequential incongruency effect is quite general, impacting the trial *n* even when the task changes (from response according to direction to response according to position) and the stimuli are different (arrows and circles). This generality of the hindrance effect caused by *n*-1 incongruency is arguably better accommodated by PRO than by CMT. This is because PRO's explanation for sequential incongruency effects relies on the activation of goals and suppression criterion impinging on abstract action plans (e.g., "respond according to stimulus position") which are in fact task-general, while CMT proposes enhancement and inhibition mechanisms that are recruited in a manner quite specific with respect to the structure of a given task's stimuli and its mapping onto the response alternatives within that task.

Even though our data seem to be better explained by PRO, there are alternative theories that could at least in part account for our results. According to some authors (Mayr et al., 2003; Nieuwenhuis et al., 2006), trial-by-trial adjustments supposedly reflecting cognitive control can be explained by associative priming. Specifically, the sequence effects could be due to the occurrence of exact stimulus-response repetitions in IC-IC and C-C sequences (benefiting processing in the second trial) and response repetitions to different stimuli in IC-C and C-IC sequences (increasing difficulty while processing the second trial). In both Mayr et al. (2003) and Nieuwenhuis et al. (2006), the sequence effects were absent in a flanker task when only sequences without exact stimulus-response repetitions or partial stimulus-response repetitions were analysed. In our experiments, we did not analyse exact stimulus-response repetitions. Concerning the conditions with and without response repetitions, the presence of associative priming effects should have been responsible for an impairment in $icC^{R=}$ trials relative to $icC^{R\neq}$ due to response repetition without stimulus repetition, a pattern we did not observe. Accordingly, our results are not explained by associative priming.

Another associative theory, the theory of event coding (TEC) (Hommel, Musseler, Aschersleben, & Prinz, 2001), argues that when we perceive an object, there is a feature-binding mechanism responsible for registering and

coding the perceivable features that integrate that object (e.g., the direction and position of an arrow). This integration or binding process is not restricted to stimulus features but includes combinations of stimulus and response features. The bindings created in the trial *n*-1 affect performance in the *n* trial, explaining the sequence effects (Hommel, 2009). According to this theory, when position-response and direction-response combinations partially mismatch the combinations occurring in previous trials, as in icC trials with response repetition, processing should be impaired when compared with situations of total alternation, as icC trials without response repetition. In total alternation sequences, the features of the trial *n*-1 are completely different from the features of the *n* trial, and therefore, there is no need for a new binding process. However, we did not find any difference between icC trials with and without response repetition, which seems to counter TEC predictions.

Associative and conflict adaptation processes may arguably both contribute to the occurrence of sequence effects (Egner, 2008). Verguts and Notebaert (2009) integrated these two processing accounts by proposing the "association by binding theory", in which cognitive control is itself seen as a binding process. After conflict detection, the cognitive control system strengthens all active connections between target stimuli and task demand units. In the following trial, the interference of irrelevant information would be reduced due to a stronger binding between the task demand unit and the input units. This theory advocates that learning of stimulus–stimulus and of stimulus–response associations are key for conflict adaptation and are therefore compatible with PRO theory.

The results of our experiments suggest the existence of an interaction between top-down processing (necessary for conflict resolution) and bottom-up processing (response and/or position repetition), in accordance with previous studies that found that both top-down and bottom-up processes contribute to the sequence effects (Egner, 2007; Notebaert et al., 2006; Notebaert & Verguts, 2007; Wuhr & Ansorge, 2005). Our observations specifically unveiled a pattern of interactions between these processing streams that mainly support PRO's account of conflict resolution, in which the intervention of top-down processing is considerably more complex than in CMT's account. This does not mean that CMT should in any manner be excluded as a valuable cognitive control theory. As noted by Funes, Lupianez, and Humphreys (2010), the mechanism (e.g.,

enhancement of task relevant information; inhibition of task irrelevant information; goal structures for supressing action plans and the criterion to predict response outcomes) that is in fact used by the cognitive control system to overcome conflict probably reflects task specificities. We propose that CMT is inadequate to provide a detailed account of cognitive control processes as they unfold during conflict tasks in which irrelevant and relevant information are integrated in the same stimulus and irrelevant information is linked to a prevalent response, such as the spatial Stroop task. For tasks in which conflict presents a similar type of complexity, PRO arguably provides a better account of cognitive control processing.

Future studies using techniques such as functional magnetic resonance imaging (fMRI) could better define the brain network involved in conflict processing in the spatial Stroop task. Also, our behavioural results suggest the development of event-related potential (ERP) studies as a means to probe the fine-grained temporal course of the sequence of events leading to conflict resolution in a spatial Stroop task. This would allow testing more-detailed hypothesis regarding the information processing events that resolve response conflict when relevant and irrelevant features for determining response are integrated within the stimulus.

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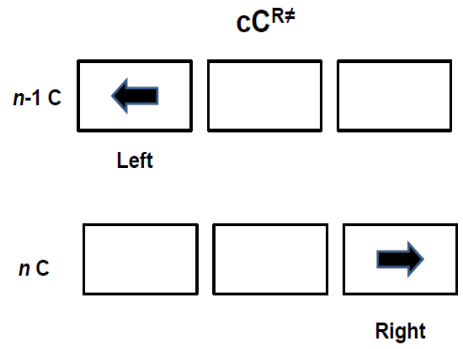
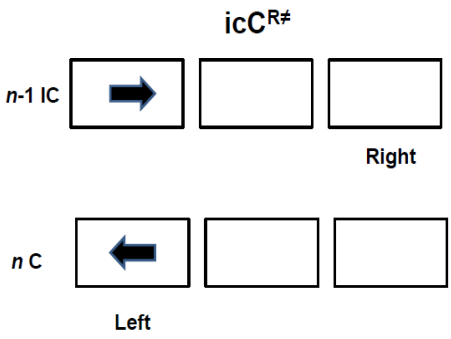
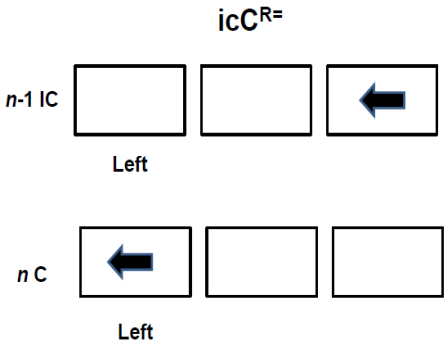
Appendix A

Table A - Visual representation of the different critical sequences studied in three Experiments.

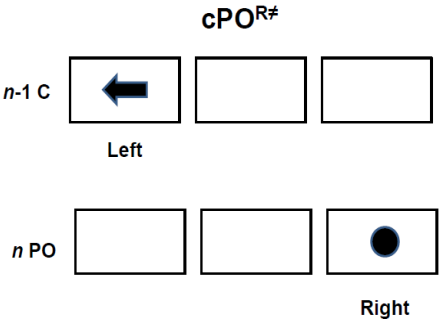
Experiment 1: Visual representation of sequence effects on current (*n*) Congruent (C) trials

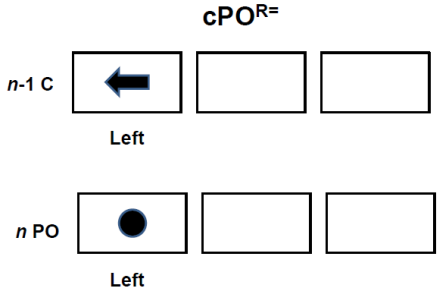


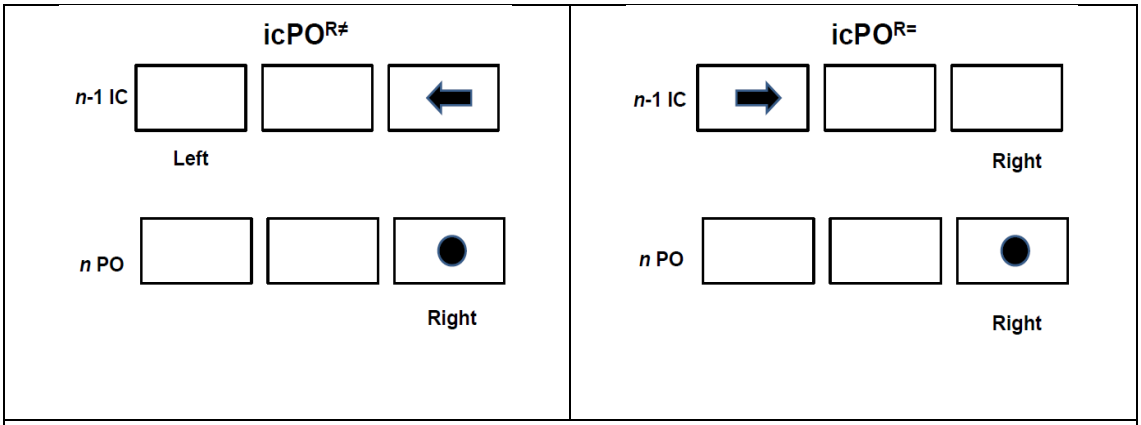




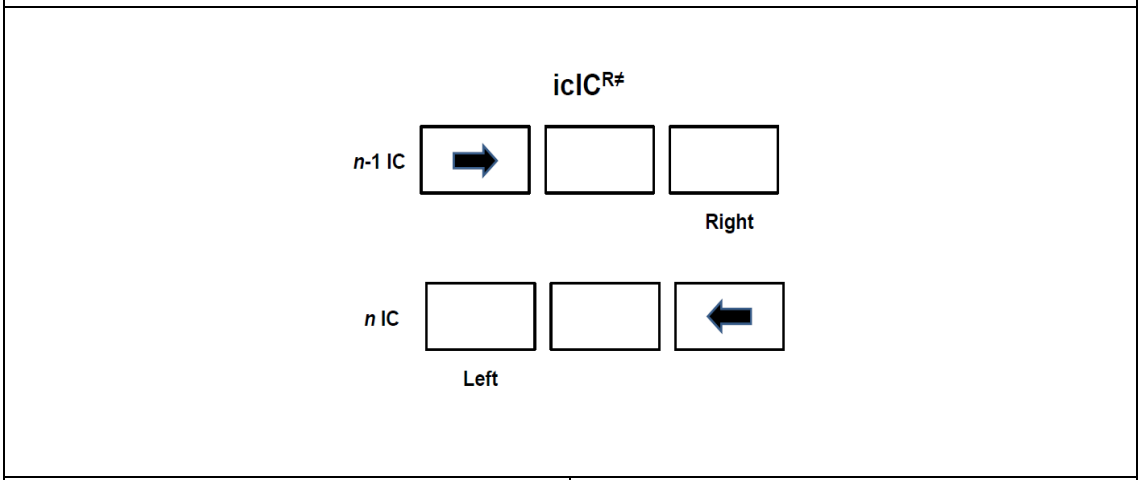
Experiment 2: Visual representation of sequence effects on current (*n*) Position-Only (PO) trials







Experiment 3: Visual representation of sequence effects on current (*n*) Incongruent (IC) trials



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