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Reduced flexibility of cognitive control: reactive, but not proactive control, underpins the congruency sequence effect

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Abstract

The congruency sequence effect (CSE) refers to facilitated conflict processing following incongruent than congruent trials, and reflects enhanced cognitive control during conflict processing. Although this effect is mostly conceived as being reactive, proactive control can also unlock it under specific circumstances according to previous studies (e.g., when an informative cue is used). However, whether or not humans can flexibly switch between these two complementing control modes remains unclear. To address this question, 55 participants completed the confound-minimized Stroop task in different blocks where the cue about the upcoming trial's congruency was either informative or not, and orthogonally to it, the cue-stimulus interval (CSI) was either short or long. We tested if the size of the CSE could change depending on the specific combination of these two factors, which would indicate that cognitive control depends on the subtle balance between reactive and proactive control, and is therefore flexible. However, results showed that the CSE was significant and comparable across the four combinations of CSI and Cue type, suggesting that it primarily stemmed from reactive control. We discuss our results against the dual mechanism of control (DMC) framework (Braver in Trends Cogn Sci 16:106–113, 2012).

Introduction

The congruency sequence effect (CSE) refers to facilitated conflict processing following incongruent compared to congruent trials (Egner, 2007), reflecting enhanced cognitive control. According to the dominant conflict monitoring model (Botvinick et al., 2001), conflict processing on trial X leads to a transient increase in cognitive control whereby it can be improved on trial X + 1, thereby resulting in the CSE. In this model, the CSE is mostly reactive, in the sense of being rapid, transient and short-lived (Clayson & Larson, 2011; Egner et al., 2010; Scherbaum et al., 2011; Yang & Pourtois, 2018; Yang et al., 2019). In agreement with this view, the size of the CSE decreases with increasing inter-stimulus intervals (ITIs, see Duthoo et al., 2014; Egner et al., 2010; van den Wildenberg et al., 2012).

However, in some situations, conflict processing can be anticipated because an informative cue about its imminent occurrence is provided to the participants, and they can adjust their level of cognitive control accordingly. Interestingly, in this situation, the CSE can also be registered, especially if the ITI is long (Alpay et al., 2009; Correa et al., 2009). In those studies, the length of the cue-stimulus interval (CSI) was usually manipulated to yield either short or long ITIs. In this situation, improved conflict processing across successive trials, as reflected by the CSE, stems from proactive control. However, unlike reactive control, proactive control is slow: additional processing time is needed to convert the information conveyed by the cue to a specific preparation that allows to deal efficiently with the upcoming conflict-related stimulus (Correa et al., 2009).

These results accord well with the dual mechanisms of control (DMC) framework (Braver, 2012), according to which reactive and proactive control are two distinct and complementing cognitive control modes. If a short ITI is used, then reactive control can guide conflict processing. Alternatively, if a longer ITI is used and, moreover, an informative cue is made available to the participants, then proactive processes can take over, and eventually determine conflict processing. In this framework, participants can flexibly switch between them, depending on both the length of the CSI and the type of cue provided to them. However, in the existing cognitive

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control literature, the evidence in favor of this flexibility remains limited, mostly because these two factors (i.e., the length of CSI and the cue type) have rarely been manipulated concurrently in the same factorial design. Moreover, existing studies have mostly focused on the congruency effect (Appelbaum et al., 2014; Bugg & Smallwood, 2016), as opposed to the CSE, which is the focus of the current study. Hence, it remains unclear whether flexible changes between reactive and proactive control can be observed for trial-by-trial adjustments during conflict processing, which provide a distinctive behavioral correlate of cognitive control. The main goal of the current study was to fill this gap. To this end, we measured the CSE using the confound-minimized Stroop task (Braem et al., 2019) and compared, using a stringent within-subject factorial design, its magnitude across different experimental conditions that differed in the balance between reactive and proactive control each time. Using the confound-minimized Stroop task, we could rule out effects of feature repetition and contingency learning to the CSE (Weissman et al., 2014; Braem et al., 2019; see also Yang & Pourtois, 2018 for a previous study using the exact same procedure). The ITI was manipulated by altering the CSI in separate blocks, which was either short (1100 ms) or long (2000 ms). Orthogonally to this manipulation, we presented participants with either an informative (100% valid) or a neutral cue regarding the (in)congruency of the upcoming Stroop stimulus. This type of cue was shown previously to promote the use of proactive control (Bugg & Smallwood, 2016). Accordingly, in half of the blocks, this cue was informative because it conveyed whether the upcoming stimulus was either congruent or incongruent. In the other half, a cue was also presented to control for the mere presentation of this visual event, but it was not informative about the (in)congruency of the upcoming Stroop stimulus.

In agreement with the DMC framework (Braver, 2012), we hypothesized that when a short CSI was used, the CSE should remain unaffected by Cue type because reactive control underlay it. However, when the CSI was long, we surmised that the CSE should be larger with an informative than a neutral cue, reflecting the engagement of proactive control in the former case. In the latter case, the long CSI (combined with the absence of an informative cue) should compromise the use of reactive control, which is short-lived. In other words, we predicted a significant interaction effect between cue type and CSI on the CSE.

Methods

Participants

Fifty-five participants (all native Dutch speaker) took part in this experiment. This sample size was estimated based on a power analysis (run in Gpower) to detect a medium effect size ($f = 0.4$) with 80% power using a $2 \times 2 \times 2 \times 2$ within-subject design. Two participants were removed from the analyses due to low accuracy (< 60%). Accordingly, the data of fifty-three participants (mean age = 23, SD = 6.3, 11 males) were available for subsequent analyses. They were compensated with 14 Euro for their participation, and all participants had a normal or corrected-to-normal vision.

Stimuli and task

Participants were seated in front of a computer monitor and performed a specific Stroop task controlling for effects of feature repetition and contingency learning (Schmidt & Weissman, 2014; Weissman et al., 2014; see Fig. 1). For each trial, a Stroop stimulus was shown in the center of the computer screen until the participant responded. Participants were instructed to identify the color of the word (i.e., color-naming task) as fast and accurate as possible by using four predefined keys of a response box. These four keys corresponded to four colors (i.e. red, blue, green, yellow). More specifically, they used their left middle finger to respond to red color, left index finger to blue color, right index finger to green color, and right middle finger to yellow color.

The Stroop stimuli consisted of four words (in Dutch) (“rood”/red, “blauw”/blue, “groen”/green, or “geel”/yellow; font size, 30 points) presented in one out of four possible colors (red, RGB: 255, 0, 0; blue, RGB: 0, 176, 240; green, RGB: 0, 255, 0; yellow, RGB: 255, 255, 0). For a given participant, each word was presented in only two of the possible four colors, however (see below). To rule out contingency learning, a four-alternative forced choice (4-AFC) task was used (Schmidt & Weissman, 2014; Weissman et al., 2014), where two pairs of S–R were created arbitrarily to balance congruent and incongruent trials. Each pair consisted of two words and two colors such that incongruent trials were created for the (incompatible) word-color association within each pair, but not across pairs. According to this rule, 8 stimuli types were created in total (instead of 16 if all combinations were constructed), corresponding to 4 stimuli for congruent trials and 4 stimuli for incongruent trials. Each word was presented equally often in the congruent and incongruent color in each block within each mapping (Mordkoff, 2012).

Reactive or proactive control was supposed to be elicited in separated blocks, by presenting either a “neutral” cue or an “informative” cue prior to the presentation of the Stroop stimulus for each trial separately (Fig. 1). Specifically, an informative cue informing about the (in)congruency of the upcoming Stroop stimulus was used to promote the use of proactive control. It could be either a black tick mark indicating congruency of the upcoming stimulus (i.e. the word meaning matched its color), or a black cross mark indicating its incongruency (i.e. the word meaning and its color mismatched with each other) (Fig. 1a). By comparison, the use of proactive control was strongly reduced by presenting a neutral cue that corresponded to a black circle throughout, without carrying

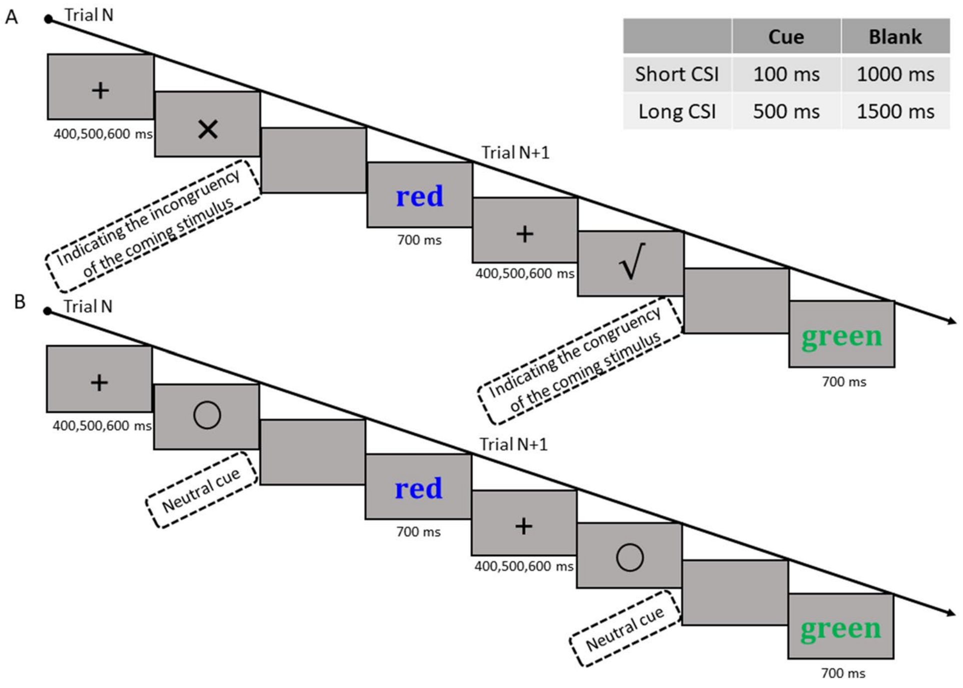

Fig. 1 Experimental procedure. Each trial started with a fixation point that was used as ITI, with a mean duration of 500 ms (range 400–600 ms). After the fixation point, the informative or neutral cue was presented for 100 ms as the short CSI condition or 500 ms as the long CSI condition. **A.** The informative cue could be either a cross mark indicating the incongruency of the upcoming stimulus, or a tick mark indicating its congruency. **B.** The neutral cue corresponded to a black circle throughout, without carrying specific information regarding the (in)congruency of the upcoming stimulus. After that, a blank screen was shown for 1000 ms (the short CSI condition) or 1500 ms (the long CSI condition), before the Stroop stimulus was presented in the center of the screen for 700 ms or until a response was given.

specific information regarding the (in)congruency of the upcoming Stroop stimulus (Fig. 1b). In this condition, participants were thus unable to prepare for (in)congruency before its onset.

Orthogonally to this manipulation, we also manipulated the CSI. Each trial started with a fixation point that was used as ITI, with a mean duration of 500 ms (range 400–600 ms). After the fixation point, for the short CSI condition, the informative or neutral cue was presented for 100 ms, followed by a blank screen shown for 1000 ms, before the Stroop stimulus was presented in the middle of the screen for 700 ms or until a response was given (see Fig. 1). For the long CSI condition, the duration of the cue was 500 ms (instead of 100 ms in the short CSI condition), and the duration of the blank screen following the cue and shown before the Stroop stimulus was set to 1500 ms (instead of 1000 ms in the short CSI condition).

Procedure

After having signed the informed consent, participants started with a practice that consisted of four blocks comprising 12 trials each, for ‘short CSI-neutral cue’, ‘short CSI-informative cue’, ‘long CSI-neutral cue’, and ‘long CSI-informative cue’, respectively. The actual experiment consisted of four sessions corresponding to four main conditions (i.e. 2 CSIs × 2 Cue types). Each session comprised three blocks (12 small blocks in total) including 125 trials each. For a given Cue type, three blocks were presented successively in triplets. For a given CSI, the two blocks were presented successively. Half of the participants started with the short CSI, while the other half started with the long CSI. Moreover, the order of Cue type was alternated across participants. At the start of each block, participants were encouraged to make accurate and fast responses. In between blocks, self-spaced breaks were allowed. Stimuli were shown in a pseudo-random order within each block to lead to the same number of cC, cI, iC and iI trials. Trial lists were prepared beforehand to avoid stimulus and response repetitions across successive trials, thereby minimizing the possible contribution of priming to the observed CSE. Stimuli presentation and data recording were controlled using E-Prime (Version 2.0; Psychology Software Tools Inc., Sharpsburg, PA).

Data analyses

Data preprocessing, visualization and analysis were carried out in R (R Core Team, 2018), using the tidyverse (Wickham, 2017), ggplot2 (Wickham, 2016), and lme4 (Bates et al., 2014) packages. For each subject separately, the first trial of each block, post-error trials, and outliers (i.e., smaller than 100 ms or larger than 3 SD from the mean) were excluded from the error rates analysis, leading to 76.9% of trials remaining (61,172 out of 79,500 trials available in total). Likewise, the first trial of each block, error trials, post-error trials, and outliers were excluded from further analyses for RT data, leading to 66.8% of trials (i.e. 53,082 out of 79,500 trials available in total). Error rates and RT data were analyzed using a generalized linear mixed model (GLMM) approach. Compared to linear mixed model (LMM), GLMM allows to use the most appropriate dependent variable (i.e. the RTs themselves instead of their natural log function in the present case) as well as meet the mathematical assumptions of the model (i.e. normality) (Lo & Andrews, 2015). More specifically, we used a GLMM with Gaussian distribution and natural log link function for RTs data, and with binomial distribution and logit link function for the error rates.

We added the random intercept for each subject as the random effect in the model. For the fixed effects of the model, four main effect (Previous congruency, Current congruency, Cue type, and CSI), six two-way interactions (Previous congruency by Current congruency, Previous congruency by Cue type, Current congruency by Cue type, Previous congruency by CSI, Current congruency by CSI, and Cue type by CSI), four three-way interactions (Previous congruency by Current congruency by Cue type, Previous congruency by Current congruency by CSI, Previous congruency by Cue type by CSI, and Current congruency by Cue type by CSI), and a four-way interaction (Previous congruency by Current congruency by Cue type by CSI) were added. We used the mean-centered deviation coding for the four factors (CSI, Cue type, Previous congruency, Current congruency). To assess the effects of each factor of interest (i.e., the main and interaction effects) on error rates and RTs, we compared models with and without that fixed effect of interest using likelihood ratio tests. For each comparison, both models included all other fixed effects that would conceivably influence the data, as well as identical random effects structures.

Exploratory analysis

Presumably, whether participants started with the long or short CSI might influence the modulation of the CSE by Cue type. To explore this possibility, we ran an auxiliary analysis where CSI order (i.e., starting either with a Short or Long CSI) was added to the GLMM as a between-subjects variable.

Table 1 Summary of fixed effects for error rates

Predictor	Estimate	SE	*z* value	Pr(>|*z*|)
(Intercept)	− 2.012	0.092	− 21.901	< 2e−16***
PreCon	− 0.101	0.024	− 4.109	3.98e−05***
CurCon	− 0.201	0.024	− 8.204	2.32e−16***
Cue	− 0.042	0.024	− 1.722	0.086
CSI	0.092	0.025	3.747	0.000***
PreCon:CurCon	− 0.114	0.049	− 2.329	0.020*
PreCon:Cue	− 0.021	0.049	− 0.429	0.668
CurCon:Cue	0.021	0.049	0.423	0.672
PreCon:CSI	− 0.001	0.049	− 0.011	0.991
CurCon:CSI	0.141	0.049	2.875	0.004**
Cue:CSI	0.034	0.049	0.695	0.487
PreCon:CurCon:Cue	0.066	0.098	0.673	0.501
PreCon:CurCon:CSI	0.100	0.098	1.017	0.309
PreCon:Cue:CSI	0.109	0.098	1.108	0.268
CurCon:Cue:CSI	− 0.004	0.098	− 0.037	0.971
PreCon:CurCon:Cue:CSI	0.054	0.197	0.272	0.786

‘***’ < 0.001; ‘**’ < 0.01; ‘*’ < 0.05; ‘.’ < 0.1; ‘’ 1

Results

Error rates

The model comparison based on the fixed effects (see Table 1) showed a significant main effect of Current congruency, $\chi^2(1) = 67.367$, $p < 0.001$, indicating lower error rates for congruent than incongruent trials. The main effect of CSI was also significant, $\chi^2(1) = 14.03$, $p = 0.0002$, indicating lower error rates for the long than the short CSI. Moreover, the two-way interaction between Previous congruency and Current congruency was significant as well, $\chi^2(1) = 5.417$, $p = 0.019$. This effect was explained by that higher error rates for iC trials compared to cC trials, $z = 4.410$, SE = 0.036, $p < 0.0001$, whereas error rates did not differ between cI and iI trials, $z = 1.272$, SE = 0.034, $p = 0.203$. However, the four-way interaction between CSI, Cue type, Previous congruency and Current congruency was not significant, $\chi^2(1) = 0.075$, $p = 0.785$.

In the exploratory analysis, the model comparison based on the fixed effects (see Table 2) showed that the four-way interaction between the Previous congruency, Current congruency, CSI, and the CSI Order was significant $\chi^2(1) = 5.402$, $p = 0.020$. To further explore it, two GLMMs with three factors (Previous congruency, Current congruency, and CSI) were computed, for each CSI

Table 2 Summary of fixed effects for error rates when the CSI order was taken into account

Predictor	Estimate	SE	*z* value	Pr(>|*z*|)
(Intercept)	− 2.018	0.086	− 23.553	< 2e−16***
PreCon	− 0.098	0.025	− 3.911	9.21e−05***
CurCon	− 0.190	0.025	− 7.652	1.97e−14***
Cue	− 0.046	0.025	− 1.851	0.064
CSI	0.112	0.025	4.506	6.60e−06***
CSI order	− 0.480	0.171	− 2.804	0.005**
PreCon:CurCon	− 0.108	0.050	− 2.187	0.029*
PreCon:Cue	− 0.012	0.050	− 0.249	0.803
CurCon:Cue	0.015	0.050	0.293	0.770
PreCon:CSI	− 0.012	0.050	− 0.239	0.811
CurCon:CSI	0.107	0.050	2.164	0.030*
Cue:CSI	0.028	0.050	0.562	0.574
PreCon:CSI order	0.059	0.050	1.189	0.234
CurCon:CSI order	0.122	0.050	2.446	0.014*
Cue:CSI order	− 0.076	0.050	− 1.511	0.131
CSI:CSI order	0.273	0.050	5.455	4.89e−08***
PreCon:CurCon:Cue	0.072	0.099	0.728	0.467
PreCon:CurCon:CSI	0.067	0.099	0.676	0.500
PreCon:Cue:CSI	0.103	0.099	1.037	0.300
CurCon:Cue:CSI	0.002	0.099	0.016	0.988
PreCon:CurCon:CSI order	0.013	0.100	0.127	0.899
PreCon:Cue:CSI order	0.123	0.100	1.236	0.216
CurCon:Cue:CSI order	− 0.062	0.100	− 0.620	0.535
PreCon:CSI:CSI order	− 0.192	0.100	− 1.924	0.054
CurCon:CSI:CSI order	− 0.428	0.100	− 4.290	1.79e−05***
Cue:CSI:CSI order	− 0.126	0.100	− 1.261	0.207
PreCon:CurCon:Cue:CSI	0.048	0.198	0.244	0.807
PreCon:CurCon:Cue:CSI order	0.150	0.210	0.749	0.454
PreCon:CurCon:CSI:CSI order	− 0.465	0.199	− 2.330	0.020*
PreCon:Cue:CSI:CSI order	− 0.034	0.198	− 0.172	0.863
CurCon:Cue:CSI:CSI order	0.045	0.199	0.227	0.821
PreCon:CurCon:Cue:CSI:CSI order	0.075	0.388	0.192	0.847

‘***’ < 0.001; ‘**’ < 0.01; ‘*’ < 0.05; ‘.’ < 0.1; ‘’ 1

order separately. When participants started with the long CSI (Fig. 3A, left panel), the interaction between Previous congruency and Current congruency was marginally significant, $\chi^2(1) = 3.262$, $p = 0.071$. The three-way interaction between Previous congruency, Current congruency, and CSI was significant, $\chi^2(1) = 5.190$, $p = 0.023$, suggesting that the CSE was significant with the long CSI, $\chi^2(1) = 8.730$, $p = 0.004$; whereas it was not with the short CSI, $\chi^2(1) = 0.132$, $p = 0.717$. By comparison, when participants started with the short CSI (Fig. 3B, left panel), the two-way interaction between Previous congruency and Current congruency was not significant, $\chi^2(1) = 1.852$, $p = 0.174$. The three-way interaction between Previous congruency, Current congruency, and CSI was not significant either, $\chi^2(1) = 1{,}342$, $p = 0.247$.

RTs

The model comparison based on the fixed effects (see Table 3) showed significant main effects of Previous congruency, $\chi^2(1) = 21.527$, $p < 0.001$, and Current congruency, $\chi^2(1) = 898.63$, $p < 0.001$, indicating each time faster RTs for congruent than incongruent trials. Also, the main effect of CSI was significant, $\chi^2(1) = 213.51$, $p < 0.001$, as was the main effect of Cue type, $\chi^2(1) = 4.934$, $p = 0.026$. These two effects indicated faster RTs for the short (compared to the long) CSI, as well as for the informative (compared to the neutral) cue. Further, the two-way interaction between Previous congruency and Current congruency was significant, $\chi^2(1) = 48.559$, $p < 0.001$. This effect was driven by faster responses for cC trials compared to iC trials, $z = 8.022$,

Table 3 Summary of fixed effects for reaction time (RT)

Predictor	Estimate	SE	*t* value	Pr(>|*z*|)
(Intercept)	6.214	0.010	597.904	< 2e−16***
PreCon	− 0.007	0.001	− 4.641	4.47e−06***
CurCon	− 0.042	0.001	− 30.107	< 2e−16***
Cue	− 0.003	0.001	− 2.223	0.026*
CSI	− 0.021	0.001	− 14.626	< 2e−16***
PreCon:CurCon	− 0.020	0.003	− 6.971	3.16e− 02***
PreCon:Cue	− 0.003	0.003	− 1.123	0.261
CurCon:Cue	− 0.009	0.003	− 3.310	0.001***
PreCon:CSI	0.004	0.003	1.373	0.170
CurCon:CSI	0.004	0.003	1.408	0.159
Cue:CSI	0.008	0.003	2.903	0.004**
PreCon:CurCon:Cue	− 0.004	0.006	− 0.688	0.491
PreCon:CurCon:CSI	− 0.003	0.006	− 0.505	0.614
PreCon:Cue:CSI	− 0.004	0.006	− 0.696	0.486
CurCon:Cue:CSI	0.008	0.006	1.369	0.171
PreCon:CurCon:Cue:CSI	− 0.011	0.011	− 0.992	0.321

‘***’ < 0.001; ‘**’ < 0.01; ‘*’ < 0.05; ‘.’ < 0.1; ‘’ 1

SE = 0.002, $p < 0.0001$, whereas responses for iI trials were marginally significant faster compared to cI trials, $z = 1.779$, SE = 0.00197, $p = 0.075$, confirming the overall presence of the CSE. The two-way interaction between Cue type and CSI was also significant, $\chi^2(1) = 8.426$, $p = 0.004$. This effect was driven by faster RTs for the informative cue compared to the neutral one for the long CSI, $z = 3.571$, SE = 0.00197, $p = 0.0004$, whereas this gain was eliminated for the short CSI, $z = 0.536$, SE = 0.002, $p = 0.5291$. In addition, the two-way interaction between Cue type and Current congruency was also significant, $\chi^2(1) = 10.955$, $p = 0.0009$. This effect was explained by slower responses for congruent trials for the neutral cue (491 ms) than the informative cue (487 ms), $z = 3.803$, SE = 0.002, $p = 0.0001$, whereas for incongruent trials, responses were comparable for the informative and neutral cues, $z = 0.836$, SE = 0.00197, $p = 0.403$. However, we did not find a significant modulation of the CSE by CSI and Cue type; instead, the CSE was appeared to be statistically comparable across the four main conditions (see Table 3 and Fig. 2).

In the exploratory analysis, the model comparison (see Table 4) showed that the three-way interaction between CSI, Cue type, and CSI Order was significant, $\chi^2(1) = 6.5789$, $p = 0.010$. Moreover and importantly, the four-way interaction between Previous congruency, Current congruency, CSI, and CSI order was significant as well, $\chi^2(1) = 5.7346$, $p = 0.0166$. To further explore it, two GLMMs including three factors (Previous congruency, Current congruency, and CSI) were computed, for each CSI order separately. When participants started with the long CSI (Fig. 3A, right panel), the interaction between Previous congruency and Current congruency was significant, $\chi^2(1) = 28.878$, $p < 0.001$. The three-way interaction between Previous congruency, Current congruency, and CSI was not significant, $\chi^2(1) = 1{,}6371$, $p = 0.201$, suggesting that the CSE was elicited irrespective of the length of the CSI. By comparison, when participants started with the short CSI (Fig. 3B, right panel), the two-way interaction between Previous congruency and Current congruency was significant, $\chi^2(1) = 19.022$, $p < 0.001$, as was the three-way interaction between Previous congruency, Current congruency, and CSI, $\chi^2(1) = 4.4628$, $p = 0.035$. This interaction showed that the CSE was significant in the short CSI, $\chi^2(1) = 19.497$, $p < 0.001$; but not in the long CSI, $\chi^2(1) = 2.589$, $p > 0.10$. Figure 4 presents the CSE scores[1] separately for the long and short CSIs, as well as depending on the CSI order (i.e., participants started either with the short or long CSI).

Discussion

The current study sought to assess whether cognitive control is flexible and depends on the balance between reactive and proactive control or not. We mostly focused on the CSE, which provides a distinctive measure of cognitive control (for a recent review, see Braem et al., 2019). To this end, we manipulated the Cue type (being either informative about the upcoming trial’s congruency or neutral) and the CSI (being either short or long) in a within-subject factorial design. Results showed that the CSE was well elicited for

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[1] The CSE score was computed using the formula: ([CI-CC)]-[II-IC]) following van Steenbergen et al. (2009).

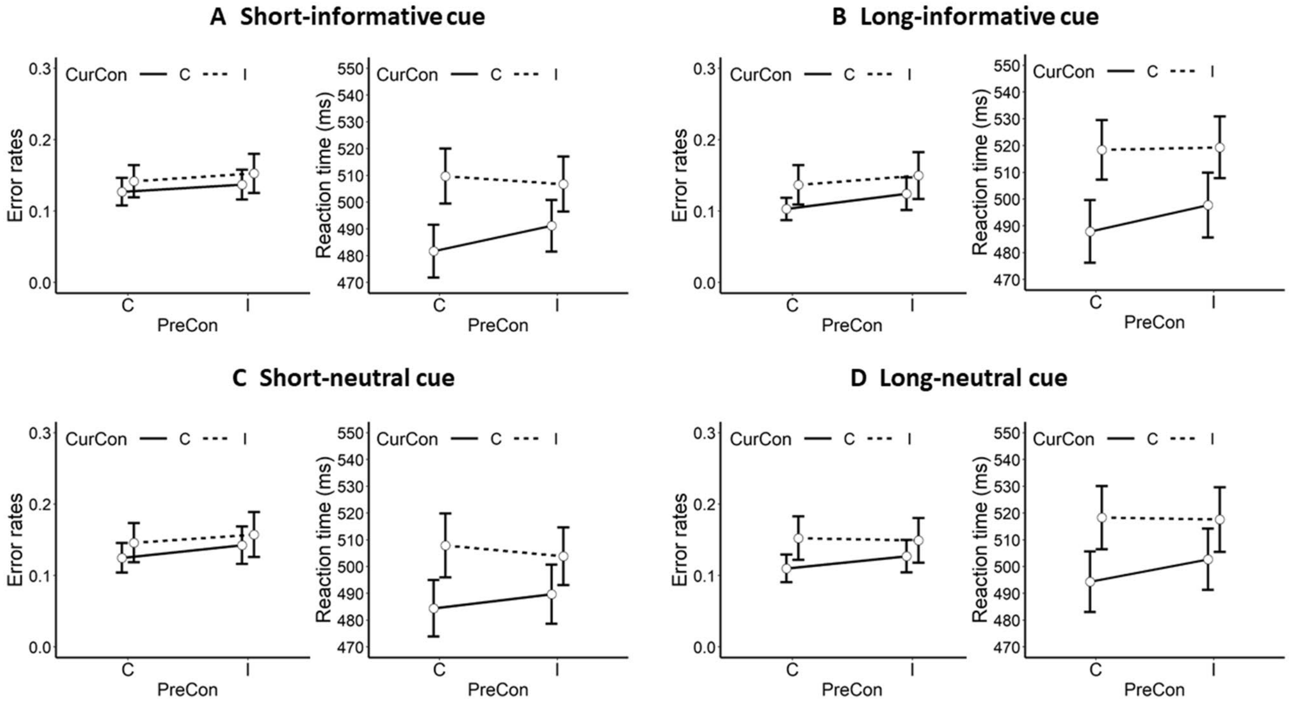


Fig. 2 Two-way interaction (between previous congruency and current congruency) results shown for each of the four main conditions (i.e. 2 CSIs × 2 Cue types) separately: short-informative cue, long-informative cue, short-neutral cue, and long-neutral cue. For each condition, the mean error rates (left panel) and reaction time (right panel) is shown. The error bar indicates 95% confidence intervals (CI).

both RTs and error rates, yet its size did not change depending on these variables. Accordingly, we failed to evidence flexibility in the balance between reactive and proactive control. Instead, our results suggest that reactive control likely offered a dominant and uniform control mode to the participants throughout the experiment, as if they could not easily switch from reactive to proactive control when a long CSI, in combination with an informative cue, was used. This reluctance to switch to, or simply use proactive control was also substantiated indirectly by our exploratory analysis, where we took CSI order into account and assessed possible variations of the CSE depending on the actual length of the CSI with which participants were initially confronted. When they started with the long CSI, the CSE was significant and comparable for the two phases of the experiment. However and interestingly, when they started with the short CSI, the CSE was observed but it disappeared when a long CSI was introduced later during the experiment. Hereafter, we discuss the implications of these new results, with a focus on the DMC model (Braver, 2012).

According to this model, CSI and Cue type are two factors that can determine whether cognitive control operates in a reactive or proactive manner. If the CSI is short, then reactive control should prevail because, even if an informative cue is provided in this "suboptimal" condition, there is no sufficient time to exploit it (Alpay et al., 2009; Horga et al., 2011). In comparison, proactive control could compensate for the rapid decay of reactive control, should the CSI be long and an informative cue made available prior to conflict processing. If true, the strength of the CSE should therefore vary depending on the actual combination of CSI and Cue type used. However, here we failed to observe this systematic modulation of the CSE across the four main conditions, despite the fact that participants did use the informative cue when it was made available to them. The significant main effects of CSI and Cue type ruled out the assumption that these two factors, Cue type and CSI, had no or little effect on conflict processing in our experiment. As expected, participants were faster when a short than long CSI was used, and also faster when the cue was informative compared to neutral. Moreover, this gain associated with the informative cue was actually only observed when a long, as opposed to short CSI was used, as reflected by the significant two-way interaction between these factors. Accordingly, we have good reasons to assume that the informative cue was processed as such by the participants, yet it was unable to influence the CSE.

Therefore, a parsimonious interpretation is that the even distribution of the CSE across the four main conditions seen in this study likely reflected the involvement of reactive control throughout, which was therefore corresponding to the default cognitive control mode. It provided an optimal and

Table 4 Summary of fixed effects for RT when the CSI order was taken into account

Predictor	Estimate	SE	*t* value	Pr(>|*z*|)
(Intercept)	6.214e+00	1.041e−02	596.893	< 2e−16***
PreCon	− 6.661e−03	1.407e−03	− 4.734	2.20e−16***
CurCon	− 4.258e−02	1.406e−03	− 30.288	< 2e−16***
Cue	− 3.049e−03	1.407e−03	− 2.167	0.030*
CSI	− 2.078e−02	1.408e−03	− 14.760	< 2e−16***
CSI order	2.265e−03	2.084e−02	0.109	0.913
PreCon:CurCon	− 1.950e−02	2.809e−03	− 6.943	3.83e−12***
PreCon:Cue	− 3.179e−03	2.811e−03	− 1.131	0.258
CurCon:Cue	− 9.388e−03	2.808e−03	− 3.343	0.001***
PreCon:CSI	3.845e−03	2.811e−03	1.368	0.171
CurCon:CSI	4.359e−03	2.808e−03	1.552	0.121
Cue:CSI	8.139e−03	2.813e−03	2.894	0.004**
PreCon:CSI order	− 5.669e−04	2.814e−03	− 0.201	0.840
CurCon:CSI order	1.471e−02	2.812e−03	5.232	1.67e−07***
Cue:CSI order	2.064e−03	2.814e−03	0.734	0.463
CSI:CSI order	1.420e−02	2.815e−03	5.042	4.60e−07***
PreCon:CurCon:Cue	− 3.915e−03	5.617e−03	− 0.697	0.486
PreCon:CurCon:CSI	− 3.330e−03	5.617e−03	− 0.593	0.553
PreCon:Cue:CSI	− 3.775e−03	5.621e−03	− 0.672	0.502
CurCon:Cue:CSI	7.752e−03	5.616e−03	1.380	0.167
PreCon:CurCon:CSI order	3.572e−03	5.618e−03	0.636	0.525
PreCon:Cue:CSI order	− 1.860e−03	5.621e−03	− 0.331	0.741
CurCon:Cue:CSI order	1.341e−06	5.616e−03	0.000	0.999
PreCon:CSI:CSI order	− 1.660e−02	5.622e−03	− 2.952	0.003**
CurCon:CSI:CSI order	− 2.984e−02	5.617e−03	− 5.312	1.80e−07***
Cue:CSI:CSI order	1.443e−02	5.626e−03	2.565	0.010*
PreCon:CurCon:Cue:CSI	− 1.150e−02	1.123e−02	− 1.024	0.306
PreCon:CurCon:Cue:CSI order	− 2.884e−02	1.123e−02	− 0.257	0.797
PreCon:CurCon:CSI:CSI order	− 2.690e−03	1.123e−02	− 2.395	0.017*
PreCon:Cue:CSI:CSI order	9.327e−03	1.124e−02	0.830	0.407
CurCon:Cue:CSI:CSI order	− 6.898e−03	1.123e−02	− 0.614	0.539
PreCon:CurCon:Cue:CSI:CSI order	− 1.712e−02	2.247e−02	− 0.762	0.446

‘***’ < 0.001; ‘**’ < 0.01; ‘*’ < 0.05; ‘.’ < 0.1; ‘’ 1

preferential strategy to deal with conflict across successive trials, but also changing contexts (Aarts & Roelofs, 2011; Aben et al., 2017; Braver, 2012; Duthoo & Notebaert, 2012). This assertion is also corroborated indirectly by the finding that the beneficial effect of the informative cue was selectively observed for congruent rather than incongruent trials in the current experiment, suggesting that when proactive control was promoted, it did not necessarily lead to a gain in conflict processing. Moreover, another implication of our new results is that a long CSI is not necessarily an inadequate condition for reactive control. In line with this interpretation, some previous studies have already reported that the CSE could still be observed even though a relatively long ITI (i.e., 3000–6000 ms) was used (Egner & Hirsch, 2005a, 2005b; Egner et al., 2007). This length is definitely longer than the 2000 ms used in this study and corresponding to the long CSI condition. In addition, in some other studies (Goldfarb & Henik, 2013), even though an informative cue was used in combination with a long CSI, no evidence was found for the involvement of proactive control.

An important contribution of our study is to show that despite being the “default” control mode, it is not unconstrained on the other hand. Instead, it appears to be influenced by other factors besides the CSI and Cue type, including capacity limitations (Shenhav et al., 2013). The results of the exploratory analysis, showing that the strength of the CSE varied depending on CSI order, lent support to this interpretation, indirectly. Participants who started with the long CSI showed a uniform CSE throughout the experiment and thus visibly experienced few difficulties to keep up an optimal reactive control mode when they moved to a more challenging situation during the second part of the

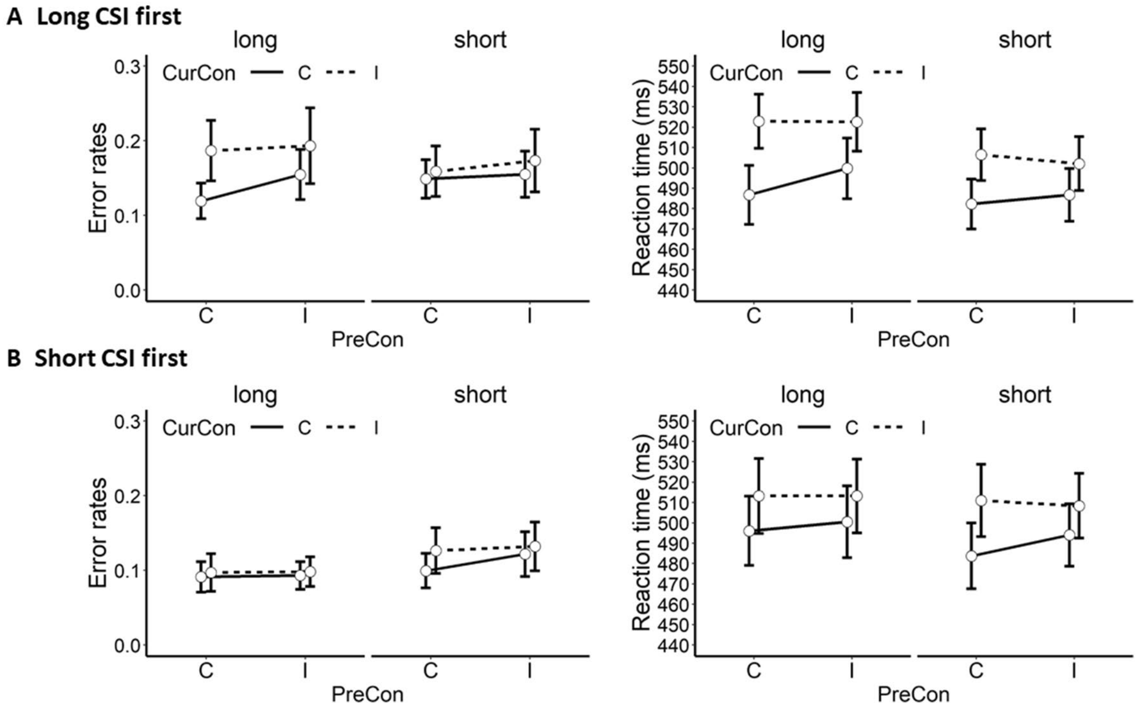
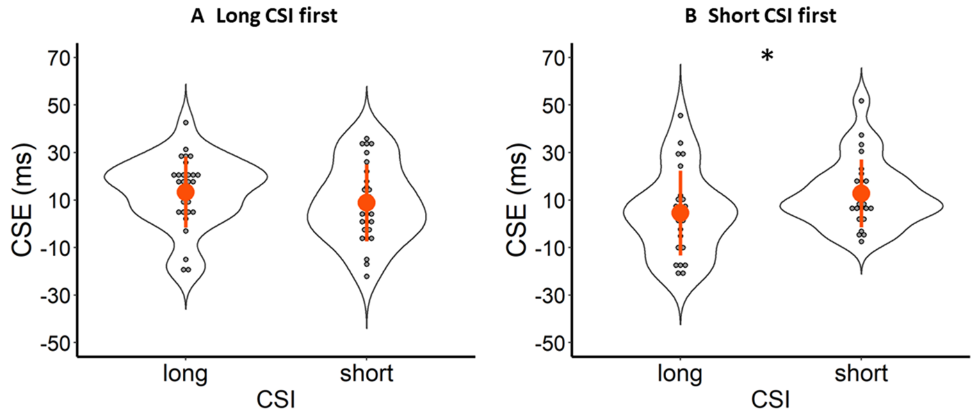


Fig. 3 The modulation of CSI to the congruency sequence effect (CSE) was modulated by CSI order. **A.** When CSI was started with long, the CSE for error rates (left panel) was only visible in the long CSI, whereas absent in the short CSI. For the RTs, the CSE was significant and comparable between short and long CSI. **B.** When CSI was started with short, the CSE for error rates (left panel) was not significant. For the RTs, the CSE was selectively present in the short CSI (early phase), whereas absent in the long CSI (late phase). The error bar indicates 95% confidence intervals (CI).

Fig. 4 The scores for the CSE. **A.** When participants started with long CSI, the mean CSE scores were significant and comparable between short and long CSI. **B.** When participants started with short CSI, the CSE was significantly reduced in long CSI compared to short one (*$p < 0.05$).



experiment (i.e., short CSI). We can therefore assume that these participants still had room to further increase reactive control when it was needed. In comparison, for the participants who started with the short CSI, they failed to maintain cognitive control at an optimal level when the CSI was longer and it thus prevented them somehow from using this reactive control mode. For these participants, reactive control was probably used intensively or excessively during the first part of the experiment, which in turn taxed cognitive resources (Locke & Braver, 2008), and eventually left little or no room for the flexible use of another control mode (i.e. proactive control) during the second part of the experiment where the CSI was long, and an informative cue provided. These results agree with the notion that cognitive control is costly and it is therefore challenging to implement it over a prolonged period of time (Shenhav et al., 2013). Although reactive control provides an efficient cognitive control mode to deal with conflict in different situations, our results suggest that it probably depends on limited resources.

Although we lack direct empirical support to corroborate this notion, we can assume that in specific circumstances, reactive control could be depleted (Hagger et al., 2010). When reactive control had to be used intensively during the first part of the experiment (because of the use of a short CSI), participants showed looser or weaker cognitive control subsequently, during the second part of it. No such change was seen for the participants who had an opposite CSI order (see also Inzlicht & Gutsell, 2007; Job et al., 2010). This depletion could result from the alteration of specific monitoring processes that are resource dependent and directly involved in the guidance of cognitive control (Inzlicht & Schmeichel, 2012). Future studies that harness electroencephalography(EEG) or imaging could help to pinpoint the cognitive control process in the prefrontal cortex, being primarily reactive, which could be depleted transiently.

To conclude, the current study suggests that cognitive control, when investigated using the CSE at the behavioral level, has limited flexibility. Instead of switching between reactive and proactive control depending on the specific trial structure (e.g., CSI) as well as specific information (e.g., Cue type) provided to them (Bugg et al., 2011; Horga et al., 2011; Karayanidis et al., 2009), participants appear to favor or prioritize reactive control to guide conflict processing in various and changing contexts. Moreover, our results also suggest that even though reactive control is a powerful cognitive mode to deal efficiently with conflict processing across successive trials, it can be depleted in specific conditions, and importantly, proactive control does not compensate for its transient decay.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the Ghent University.

Informed consent Informed consent was obtained from all individual participants included in the study.

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