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OBSERVATION

Reconciling Cognitive-Control and Episodic-Retrieval Accounts of Sequential Conflict Modulation: Binding of Control-States Into Event-Files

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How do we manage to shield our goals against distraction? Traditionally, this ability has been attributed to top-down cognitive control, which is assumed to monitor for and intervene in case of response conflicts. However, this account has been challenged by episodic-retrieval views, which attribute sequential modulations of conflict effects to bottom-up memory for stimulus and response features. Here we tested a new theory suggesting that that control and retrieval accounts are no alternatives but, rather, 2 sides of the same coin. According to this view, the control parameter can become stored in event files, together with stimulus, response, and context codes, so that cognitive control operations, independently from the stimulus-response codes the operate on, can come under mnemonic control. Using a novel design that eliminates any stimulus and response binding and at the same time disentangles conflict and retrieval of control states, we provide the strongest evidence to date that abstract control parameters are stored into trial-specific event files.

Public Significance Statement

This study suggests that episodic memory stores a snapshot of internal attentional states (e.g., focused attention) together with contextual information. Reencounter of the same context triggers an automatic retrieval of the previous attentional states. It shows that memory aids control operations by automatizing and tailoring them to the situational circumstances.

Keywords: cognitive control, feature binding, sequential modulations of conflict, conflict adaptation, conflict monitoring

How do we manage to shield our goals against distractions and temptations? Traditionally, this ability has been attributed to top-down cognitive control, which is assumed to monitor for and intervene in case of response conflicts (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Such interventions have been taken to be reflected in sequential modulations of congruency/compatibility effects in conflict tasks. If stimuli create conflict by activating more than one response in a trial, responses are slower and less accurate. Interestingly, these conflict effects are reduced in size in trials that follow a conflict trial (Egner, 2007; Gratton, Coles, & Donchin, 1992), suggesting that the recent experience of conflict leads to a dynamic upregulation of cognitive control.

However, the control-upregulation account has been challenged by episodic-retrieval views (Hommel, Proctor, & Vu, 2004; Mayr,

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David Dignath and Andrea Kiesel developed the study concept. David Dignath and Lea Johannsen contributed to the study design. Testing and data collection were performed by David Dignath and Lea Johannsen. David Dignath performed the data analysis and interpretation and drafted the manuscript, and Lea Johannsen. Bernhard Hommel and Andrea Kiesel provided critical revisions. All authors approved the final version of the manuscript for submission.

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Awh, & Laurey, 2003), which attribute sequential modulations of conflict effects to particular patterns of stimulus and response repetition/alternation. More specifically, when using small stimulus sets, performance might be better in conflict trials following conflict and nonconflict trials following nonconflict compared with conflict trials following nonconflict and nonconflict trials following conflict because stimulus and response features are either the same or completely altered in the former conditions but are recombined in the latter conditions (thus leading to retrieval of misleading stimulus or response codes or event files)—as also observed in nonconflict tasks (Hommel, 2004).

Here we tested the possibility that control and retrieval accounts are no alternatives but, rather, two sides of the same coin. Following recent theoretical accounts suggesting that abstract control parameters (such as the breadth of the attentional focus, Goschke, 2000) become stored in event files, together with stimulus, response, and context codes, so that instances of cognitive control operations can come under mnemonic control (Egner, 2014; Schumacher & Hazeltine, 2016; Spapé & Hommel, 2008; Waszak, Hommel, & Allport, 2003; see also Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010). If so, repeating any kind of feature that was also present in the previous trial might retrieve the previous control parameter and reinstantiate the corresponding control state—which should be more focused after a challenging conflict trial. Interestingly, this possibility is consistent with the recent observation that sequential conflict modulation is associated with activity in the anterior hippocampus, a structure subserving the integration and retrieval of context-dependent memories (Jiang, Brashier, & Egner, 2015).

We aimed to provide direct evidence for the assumption that sequential conflict modulation can be affected by the retrieval of control parameters. To disentangle conflict and retrieval effects, we separated the stimulus dimension that introduced the response conflict from the stimulus dimension that was hypothesized to retrieve the previous event file (which was supposed to contain the control parameter; see Figure 1). We also went beyond previous relevant research (e.g., Braem, Hickey, Duthoo, & Notebaert, 2014; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011; Spapé et al., 2008) by using a new design that eliminated any S-R repetitions (Weissman, Jiang, & Egner, 2014). Consequently, the only effect that the repetition/alternation of the (entirely irrelevant) context feature could have was the retrieval of the previous control parameter. If repeating the context feature would indeed retrieve the previous control parameter or state, this should result in a larger sequential modulation effect.

Method

Raw individual data and analysis scripts can be found on the Open Science Framework (OSF; https://osf.io/s8uzt/?view_only=7c9d62df6a7946bb8999e4be0e4c2bb1).

Participants

Thirty-nine volunteers (29 women, $M = 25.05$ years; range: 19–34) participated in Experiment (Exp.) 1. Sample size was based on an unpublished pilot study. Exp. 2 used different stimulus material to provide a conceptual replication. For Exp. 2, hypotheses, experimental methods, and analysis were preregistered on the OSF (https://osf.io/q4e3n/register/565fb3678c5e4a66b5582f67). Forty-eight volunteers (34 women, $M = 25.00$ years; range: 18–51 years) participated and sample size was based on the effect size observed for the relevant three-way interaction in Exp. 1.

A priori exclusion criteria were identical for both experiments: Participants with more than 50% error were defined as outlier (random performance in a two-alternative, forced-choice task). From the remaining sample, all participants with a mean error rate above 3 *SD* were treated as outliers. Furthermore, only participants who stated in the debriefing that they used the right hand as instructed were included. No participant was excluded based on these criteria in Exp. 1, two participants were excluded in Exp. 2 because of random performance and more than 3 *SD* errors.

Stimuli, Task and Design

Stimulus presentation and response-data collection were controlled by E-Prime (version 2.0.10.353; Schneider, Eschman, & Zuccolotto, 2002) on a 24-in. color monitor (1024 × 768 pixels, 144 Hz), and it was the same in both experiments unless stated otherwise. At the beginning of each block, a fixation cross (0.48° × 0.48°) appeared in the middle of the screen for 2,000 ms. Each trial started with a fixation cross appearing for 201 ms, followed by a task-irrelevant distractor for 139 ms, and a blank screen for 35 ms. Then the target appeared for 139 ms, followed by a blank screen for 1701 ms. Participants responded to the value (Exp. 1) or color (Exp. 2) of the target by pressing the *d*' f, g, or h key on a QWERTZ keyboard with their right index, middle, ring, and little finger. The stimulus-key mapping was fixed in Exp. 1 (values increasing from left to right) but was counterbalanced in Exp. 2 using a Latin square. In case of an incorrect or missing response (within a response window of 1,500 ms after target onset), a red screen presented for 201 ms indicated an error. A trial ended with a blank screen presented until the total trial duration of 2,215 ms was reached.

Distractors and targets varied on two dimensions: format (serving as context) and value (to induce response conflict in incongruent trials). In both experiments, the distractor was larger than the target. In Exp. 1, the distractor was either a word or a digit (context), and it was either the same or different from the target (which always appeared in the same format as the distractor) that followed. In Exp. 1, the numbers 3, 4, 5, and 6 served as distractor and target stimuli and were presented either as an Arabic digit (3, 4, 5, 6; distractor: 1.24° × 1.91°, 1.24° × 1.81°, 1.24° × 1.81°, 1.24° × 1.91°; target: 0.76° × 1.17°, 0.76° × 1.15°, 0.76° × 1.15°, 0.76° × 1.17°) or as the corresponding German word (drei, vier, fünf, sechs; distractor: 2.39° × 1.15°, 2.67° × 1.15°, 2.77° × 1.15°, 4.10° × 1,15°; target: 1.81° × 0.76°, 1.91° × 0.76°, 2.67° × 0.76°), in white on a black background and in bold Arial font. In Exp. 2, the colors red, blue, green, and yellow served as distractor and target stimuli. Stimuli were presented either as color patches (RGB: 255, 0, 0; 0, 191, 255; 0, 128, 0; 255, 255, 0; distractor: 1.53° × 1.53°; target: 0.95° × 0.95°) or as the corresponding German word (rot, blau, grün, gelb; distractor: 1.91° × 1.10°, 2.86° × 1.15°, 3.15° × 1.38°, 2.96° × 1.43°; target: 1.34° × 0.76°, 1.91° × 0.76°, 2.10° × 0.91°, 2.01° × 0.95°).

To avoid stimulus and response repetitions, we divided stimuli and responses into sets of two independent two-alternative,

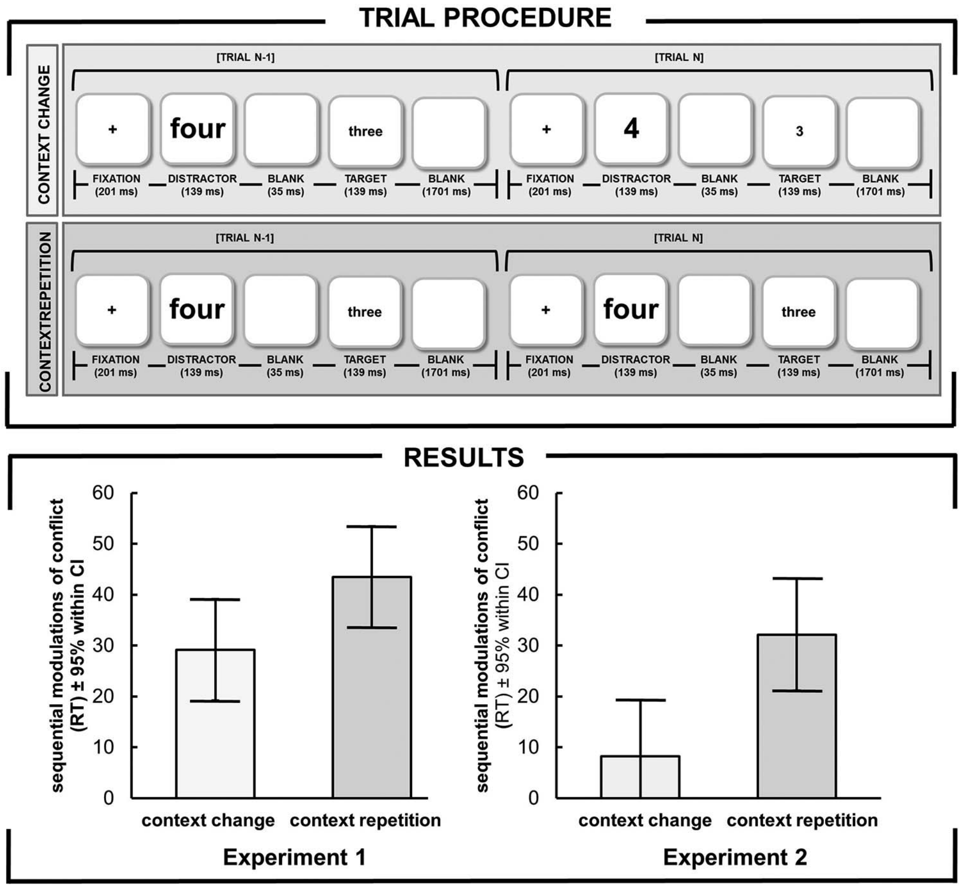

Figure 1. Upper panel: Trial sequences in Experiment 1. In each trial, participants had to identify a target number that was preceded by an irrelevant distractor number. Context was indicated by the format of the target and distractor number (Arabic number vs. spelled-out number word). Context transition was manipulated by presenting distractor and target in two consecutive trials either in different (context change) or the same format (context repetition). The trial sequence in Experiment 2 (not shown) was identical but used a different task and stimuli. Participants had to identify a target color preceded by an irrelevant distractor color. Context was indicated by the format of the distractor and target color (color patch vs. spelled-out color word). In the lower panel, results of Exp. 1 and Exp. 2 show sequential modulation of conflict effects for context change trials and context repetition trials. Error bars indicate 95% confidence intervals for the within-subject comparison between context change and context repetition trials.

forced-choice tasks that alternated every trial (assignment of stimulus-to-set was counterbalanced across participants). Distractor and target were always from the same stimulus set to avoid negative priming. To control for contingency learning, each target was preceded equally often by incongruent and congruent distractors.

Trials were first-order counterbalanced using custom MATLAB scripts (The MathWorks, Inc., Natick, Massachusetts, United States) to produce an even distribution of all relevant congruency sequences (congruent in N-1 ▷ congruent in N; incongruent in N-1 ▷ congruent in N; congruent in N-1 ▷ incongruent in N; incongruent in N-1 ▷ incongruent in N) separately for each of the four possible context transitions (word context in N-1 ▷ word context in N; symbol context in N-1 ▷ word context in N; word context in N-1 ▷ symbol context in N; symbol context in N-1 ▷ symbol context in N-1) across each run of 96 trials.

Procedure

Participants gave informed written consent before the experiment. They were tested in individual testing rooms with a viewing distance of approximate 60 cm to the monitor. All instructions were presented on the screen and both speed and accuracy was emphasized. Participants started with 64 practice trials. The main experiment consisted of 24 blocks with 48 trials each, with self-paced breaks between the blocks. At the end of the experiment, participants stated whether they used the fingers of their right hand as instructed.

Results

We discarded practice trials, the first trial in each block, and posterror trials (Exp.1: 6.6%; Exp. 2: 9.8%) from all analyses and trials with erroneous responses (Exp.1: 7.9%; Exp. 2: 13.6%)

and reaction times (RTs) that exceeded more than 3 *SD* from the cell mean for each condition (Exp. 1 and Exp. 2 $< 0.1\%$) from the RT analysis. We analyzed mean RTs and error rates of both experiments with a repeated-measures ANOVA with the factors congruency in N (congruent, incongruent), congruency in N-1 (congruent, incongruent), and context transition (change, repeat). The significance criterion was set to $p < .05$ for all analyses. Nonsignificant effects are only reported in case of theoretical relevance. Standardized effect sizes (Cohen's dz and η_p^2) are reported when appropriate. RT means in Exp. 1 were calculated based on $M = 120$ observations ($SD = 12.43$) and in Exp. 2 based on $M = 111$ observations ($SD = 12.43$). Table 1 shows the condition means for RTs and error rates.

We asked whether repeating a task-irrelevant context from trial N-1 to trial *N* might retrieve control parameters/states, which predicts that the sequential conflict modulation should be larger with context repetition than with context change. As Figure 1 (lower panel) shows, this was indeed the case. The three-way interaction among congruency in N, congruency in N-1 and context transition was significant for RTs in Exp. 1, $F(1, 38) = 8.43$, $p = .006$, $\eta_p^2 = .18$, and Exp. 2, $F(1, 45) = 19.11$, $p < .001$, $\eta_p^2 = .29$. This interaction effect was driven by a larger sequential conflict modulation for context repetitions (Exp.1: $\Delta = 43$ ms, $t(38) = 7.06$, $p < .001$, $dz = 1.13$; Exp. 2: $\Delta = 32$ ms, $t(45) = 7.13$, $p < .001$, $dz = 1.05$) than for context changes (Exp.1: $\Delta = 29$ ms, $t(38) = 4.70$, $p < .001$, $dz = 0.75$; Exp. 2: $\Delta = 8$ ms, $t(45) = 1.71$, $p = .094$, $dz = 0.25$).

The RT ANOVAs yielded further expected results: main effects of congruency in *N* (Exp.1: $\Delta = 144$ ms, $F[1, 38] = 231.55$, $p < .001$, $\eta_p^2 = .86$; Exp.2: $\Delta = 137$ ms, $F[1, 45] = 448.69$, $p < .001$, $\eta_p^2 = .91$) and congruency in N-1, indicating a postconflict slowing effect (Exp.1: $\Delta = 10$ ms, $F[1, 38] = 35.88$, $p < .001$, $\eta_p^2 = .49$; Exp. 2: $\Delta = 6$ ms, $F[1, 45] = 13.02$, $p < .001$, $\eta_p^2 = .22$; Ullsperger, Bylsma, & Botvinick, 2005). Significant two-way interactions showed an overall sequential conflict modulation, that is, the congruency effect was smaller following incongruent compared with congruent trials (Exp.1: $\Delta = 36$ ms, $F[1, 38] = 41.02$, $p < .001$, $\eta_p^2 = .52$; Exp. 2: $\Delta = 20$ ms, $F[1, 45] = 28.43$, $p < .001$, $\eta_p^2 = .38$). Additionally, the congruency effect was larger following context repetition than following context switches (Exp.1: $\Delta = 12$ ms, $F[1, 38] = 12.28$, $p = .001$, $\eta_p^2 = .24$; Exp. 2: $\Delta = 10$ ms, $F[1, 45] = 12.96$, $p = .001$, $\eta_p^2 = .22$). And postconflict slowing was larger after context repetition than following context changes but only in Exp. 2 ($\Delta = 8$ ms, $F[1, 45] = 5.15$, $p = .023$, $\eta_p^2 = .11$).

A larger sequential conflict modulation for context repetitions than context changes could be due to an unspecific distraction caused by changing the presentation format of the stimuli. However, this seems unlikely becaue switch costs for context changes compared with context repetitions were virtually absent in our study (Exp. 1: $\Delta = 1$ ms, $F < 1$; Exp. 2: $\Delta = 1$ ms, $F < 1$), and there was no significant correlation between switch costs and the difference between sequential conflict modulation in context repeat and change trials, Exp. 1: $r(37) = -.071$, $p = .668$; Exp. 2: $r(44) = .030$ $p = .855$, ruling out that the present results were driven by a subset of participants with larger perceptual switch costs.

The same analyses of the error data indicated only significant main effects for congruency in *N* (Exp. 1: $F[1, 38] = 18.99$, $p < .001$, $\eta_p^2 = .33$; Exp. 2: $F[1, 45] = 29.68$, $p < .001$, $\eta_p^2 = .39$) and congruency in N-1, (only Exp. 1: $F[1, 38] = 7.79$, $p = .008$, $\eta_p^2 = .17$). No other effects were significant.

Discussion

This study tested a new integrative account to cognitive control, according to which top-down control and stimulus-induced retrieval do not represent alternative, competing routes to action control but, rather, complementary components of an integrated control system (Egner, 2014; Hommel & Wiers, 2017). Results from two experiments (one preregistered) showed stronger sequential modulations of response-conflict effects when context cues repeated from one trial to another. The present results fit with studies that investigated learning of long-lasting response-conflict modulations (i.e., context specific proportion congruency effects; Brosowsky & Crump, 2018; Crump, Gong, & Milliken, 2006;

Table 1
Congruency and Conflict-Adaptation Effects as a Function of Condition

Trial type	Experiment 1		Experiment 2	
	RT (ms)	Errors (%)	RT (ms)	Errors (%)
Context repetition				
Congruent trial following a congruent trial (cC)	511	6.0	611	9.6
Congruent trial following an incongruent trial (iC)	543	5.7	637	9.2
Incongruent trial following a congruent trial (cI)	683	8.8	769	12.2
Incongruent trial following an incongruent trial (iI)	672	7.2	763	11.9
Sequential modulation of conflict effect	43	1.3	32	−.1
Context change				
Congruent trial following a congruent trial (cC)	522	5.9	627	10.1
Congruent trial following an incongruent trial (iC)	546	5.5	633	12.4
Incongruent trial following a congruent trial (cI)	675	9.1	763	9.3
Incongruent trial following an incongruent trial (iI)	670	7.9	761	11.5
Sequential modulation of conflict effect	29	.8	8	.1

Note. RT = reaction time. Sequential modulation of conflict effects were defined as the difference in reaction times or error rates between the congruency effect after previously congruent trials and the congruency effect after previously incongruent trials (cI-cC)–(iI-iC).

Wendt & Kiesel, 2011; Zhang, Kiesel, & Dignath, 2019). However, this line of research used sustained learning of context-control states associations, and it is currently unclear whether this relates to transient binding (2017a; Moeller & Frings, 2017b). Future research could test in more detail whether binding and learning of control-states share similar mechanisms.

The present results also might be of interest to the debate whether sequential modulations of conflict effects generalize across different tasks (e.g., Freitas & Clark, 2015; Rey-Mermet & Gade, 2016) or whether they are specific to a single task (e.g., Funes, Lupiáñez, & Humphreys, 2010; Kiesel, Kunde, & Hoffmann, 2006) with no consensus so far (for a review, see Braem, Abrahamse, Duthoo, & Notebaert, 2014; see also Schuch, Dignath, Steinhauser, & Janczyk, 2019). Possibly, evidence for task specificity might not so much reflect the limits of control but rather a failure to retrieve previous control states when tasks and contexts change (cf. Neill, 2007). For instance, most studies that reported task-specific effects used a version of the task-switching protocol in which stimuli and responses change across trials or in which attention to repeating stimuli has to be switched. Arguably, such situations significantly reduce the number and the strength of retrieval cues from one trial to another. Interestingly, most studies that observed task-general effects used either tasks that shared relevant stimulus dimension (Notebaert & Verguts, 2008) or presented both task simultaneously (Rey-Mermet et al., 2016). It seems plausible that under such conditions, control states that became bound to stimuli in one task could be retrieved more easily during the other task because the relevant stimulus feature repeated and functioned as retrieval cues.

In contrast to previous research on sequential modulations of response-conflict, our design eliminated any confounds in terms of stimulus and response repetitions. Theoretically, this is important because the very notion of a control-state binding requires that effects cannot be attributed to other types of binding. Therefore, the present results can be taken as a first demonstration that abstract control parameters and context cues are stored into trial-specific event files (Egner, 2014), which are then retrieved upon repetition of the context cue. This retrieval, we argue, tends to reinstantiate the previous control state, which is likely to be more focused on relevant stimuli after a conflict trial so that the impact of conflict is reduced. This view departs from the traditional top-down view of control: Once control has been upregulated, the control state becomes bound into an event file and later retrieval does not require further control adjustments. However, it also differs significantly from the modal view of bottom-up control because binding and retrieval are not limited to stimulus and response codes but can also comprise abstract instances of control. This suggests that stimulus-driven retrieval does not need to challenge cognitive control but may actually make control operations more adaptive by automatizing and tailoring them to the situational circumstances (Hommel, 2000).

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