The Effect of N–3 on N–2 Repetition Costs in Task Switching

Stefanie Schuch[1] & James A. Grange[2]*

[1] RWTH Aachen, Germany

[2] Keele University, UK

* Both authors contributed equally to this work

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Address for correspondence:

Stefanie Schuch

Institute of Psychology

RWTH Aachen University

Jaegerstrasse 17/19

52066 Aachen, Germany

Tel: +49 (0) 241 8093543

Email: schuch@psych.rwth-aachen.de

Abstract

N–2 task repetition cost is a response time and error cost returning to a task recently performed after one intervening trial (i.e. an AB*A* task sequence) compared to returning to a task not recently performed (i.e., a CB*A* task sequence). This cost is considered a robust measure of inhibitory control during task switching. The present paper reports a novel sequential effect of n–2 task repetitions when trial n–3 is taken into consideration. In particular, performance is better in trials *preceded* by an n–2 repetition than in trials *preceded* by an n–2 switch. That is, performance is better in BAB*A* sequences (where trial n–1 was an n–2 repetition) than in CAB*A* sequences (where trial n–1 was an n–2 switch). Likewise, performance is better in BCB*A* (where trial n–1 was an n–2 repetition) than in ACB*A* or DCB*A* sequences (were trial n–1 were n–2 switches). Evidence for this new n–3 effect is provided by a mini meta-analysis of a set of published data, as well as two new experiments applying a different paradigm. We suggest that this new effect reflects trial-by-trial modulation of cognitive control: Task conflict is higher in n–2 repetitions than in n–2 switches; therefore, cognitive control is increased in trials following n–2 repetitions, leading to improved performance. This facilitating effect of previous task conflict is discussed with respect to current theories on cognitive control.

(242 words)

Keywords: Task switching, backward inhibition, cognitive control, sequential effects

The Effect of N–3 on N–2 Repetition Costs in Task Switching

The task switching paradigm has become a popular tool with which to measure cognitive control processes (Grange & Houghton, 2014; Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). One component cognitive control process thought to aid task switching is inhibition (Koch, Gade, Schuch, & Philipp, 2010; Mayr, 2007). Evidence for inhibition in task switching arises from the backward inhibition paradigm (Mayr & Keele, 2000). In this paradigm, participants switch between three tasks; response times (RTs) are found to be slower when returning to a recently executed task (e.g., an AB*A* sequence) compared to returning to a task not recently performed (CB*A* sequence). These *n–2 repetition costs* are thought to reflect the persisting inhibition of task '*A*' when it was disengaged at n–1. The evidence that these costs reflect inhibition is strong (Koch et al., 2010), and they are—to date—robust against non-inhibitory explanations (Mayr, 2007).

The purpose of the present paper is to report a new sequential effect in backward inhibition paradigms when sequential effects from n–3 are taken into consideration. Specifically, we report that trials *following* n–2 repetitions are performed faster than trials following n–2 switches. That is, BAB*A* sequences (n–2 repetition following n–2 repetition) are performed faster than CAB*A* sequences (n–2 repetition following n–2 switch). Likewise, ACB*A* sequences (n–2 switch following n–2 repetition) are performed faster than BCB*A* sequences (n–2 switch following n–2 switch).[1]

We begin by reporting the new sequential effect by re-analysing published data (Grange & Houghton, 2010). Data from two new experiments with different task demands are then reported, showing the generality of the new effect. We suggest that this effect is due to increased cognitive control triggered by task conflict, an idea derived from theories of

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[1] Note that the last letter *A* always refers to the task on the current trial, and therefore is put in italics. The preceding letters refer to the tasks that occurred in the preceding trials. For instance, in a CAB*A* sequence, task B was performed in n–1, task A in n–2, and task C in n–3. Also note that A, B, and C are only placeholders and can refer to any task.

conflict adaption in the cognitive control literature (Botvinick, Braver, Barch, Carter, & Cohen, 2001).

Re-analysis of Grange & Houghton (2010)

Overview of Paradigm

Grange and Houghton (2010) used a target-localization paradigm wherein participants had to respond to the location of a pre-determined target among four possible targets, each with a different visual property (in one condition the targets were ovals: one was shaded, one had a thickened border, one was angled; the fourth was a neutral oval always present as a distractor and never required a response). Targets were positioned with one target in each corner of the screen, and spatial responses were collected via a keyboard (D = top left; C = bottom-left; J = top right; N = bottom right).

Participants knew which target was relevant on the current trial by means of a valid cue; for example, if presented with a square, participants were required to search for the shaded target, a triangle cued the bordered target, and an octagon cued the angled target. These cue–target pairings rely on participants learning arbitrary, *unrelated*, relationships between the cues and targets (see also Houghton, Pritchard, & Grange, 2009). This was contrasted with a second condition where the cues and targets were *related*: the target display now consisted of a square, a triangle, and an octagon (still with the neutral oval distractor). In this condition, participants merely respond to the location of the target that matched the cue (square cue means search for a square target, etc.). Participants were exposed to both cue-types within the same experimental session, with one cue-type presented in the first half, switching at the mid-way point of the experiment. Each half of the experiment consisted of 10 blocks of 42 trials, with a self-paced rest after each block. Task repetitions were not allowed. The results reported in Grange and Houghton (2010) showed statistically significant n–2 repetition costs for unrelated cues and no statistically significant n–2 repetition cost for related cues.

In a first step, to check whether the effect of n–3 on n–2 repetition costs is robust across experiments, we performed a mini meta-analysis (Cumming, 2012, 2014) on the experiments reported in Grange and Houghton (2010) that showed n–2 repetition costs. Having shown that the effect is robust, in a second step, a factorial re-analysis of the data from Grange and Houghton (2010) is provided.

Mini meta-analysis of the data from Grange & Houghton (2010)

New trimming procedures were required on the raw data to account for the sequential comparison back to n–3 (i.e., a comparison across four trials). Specifically, error trials were removed as well as the *three* trials following an error (cf., two trials removed in standard analyses); additionally, the first three trials from each experimental block were removed. RT outliers were identified as RTs that fell above 2.5 standard deviations of each participant's mean for each cell of the experimental design; these trials were also removed.

We find slower RTs to CAB*A* sequences than to BAB*A* sequences across all five experimental conditions in Grange and Houghton that produced n–2 repetition costs (see Figure 1). A forest-plot of the difference in RT (CAB*A* – BAB*A*) can be found in Figure 1, with their 95% confidence intervals. The mini meta-analysis (Cumming, 2012) of these five data points was performed using a mixed-effects[2] model; the result of this meta-analysis can also be seen on the forest plot, together with its 95% confidence interval. Note there is a consistent finding of increased RTs for CAB*A* sequences, reflecting the new effect. The mini meta-analysis estimates the difference in RT between CAB*A* and BAB*A* sequences to be 42ms, 95% CI [30, 54].

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[2] We note that a mixed-effects model was used as a conservative measure as the n–2 repetition cost from the switched-cues of Grange and Houghton's (2010) Experiment 1 was so large in comparison to the other studies. However, analysis demonstrated the heterogeneity of data between studies was very low ($Q = 5.46$, $df = 4$, $p = .2431$, $I^2 = 26.76\%$); as such, the use of a fixed-effects model produces qualitatively identical results.

Insert Figure 1 about here

Figure 2 is a similar forest plot, but plotting the difference in RT between ACB*A* sequences and BAB*A* sequences in the same five experimental conditions from Grange and Houghton (2010), again with a mini meta-analysis using a mixed-effects model[3]. Note that there is a consistent finding of slower RTs for ACB*A* than for BCB*A* sequences, reflecting the new effect. The mini meta-analysis estimates the difference in RT between ACB*A* and BCB*A* sequences to be 59ms, 95% CI [45, 73].

Insert Figure 2 about here

Factorial re-analysis of the data from Grange & Houghton (2010)

In a next step, the data that had entered the mini meta-analysis were re-analysed using a full factorial design with the factors “current n–2 repetition” and “previous n–2 repetition”. We performed five separate ANOVAs with the factors as described in *Design* below (one for each condition in Grange and Houghton entered into the mini meta-analysis).

Design. A 2x2 design with the within-subject factors *current n–2 repetition* (repetition vs. switch) and *previous n–2 repetition* (repetition vs. switch) was applied. Task sequences of the types BAB*A* and CAB*A* were classified as current n–2 repetitions, sequences of the types BCB*A* and ACB*A* as current n–2 switches. At the same time, BAB*A* and BCB*A* were classified as previous n–2 repetitions, and CAB*A* and ACB*A* as previous n–2 switches. The dependent variables were response times (RTs) and error rates (%).

Results. The results of all of the ANOVAs for RTs are shown in Table 1, and the descriptive statistics of each condition are in Table 2. The mean RTs—averaged across conditions—can be seen in Figure 3. As can be seen, there was a very consistent pattern of results across all conditions. For all, there was a significant main effect of *current n–2 repetition*, with current n–2 repetitions being slower (718ms, averaged across all five

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[3] Heterogeneity of scores again was very low ($Q = 5.46$, $df = 4$, $p=.2431$, $I^2 = 26.77\%$). Thus, the model used is quantitatively identical to a fixed-effects model.

conditions) than current n–2 switches (688ms), replicating the standard n–2 repetition cost. There were also consistent main effects of *previous n–2 repetition*, with previous n–2 repetitions being faster (675ms) than previous n–2 switches (731ms). There was also consistently no interaction across all of the conditions. The corresponding two-way ANOVAs on error data did not reveal any significant effects.

Insert Tables 1 and 2 about here

Insert Figure 3 about here

Discussion

Re-analysis of data from Grange and Houghton (2010) has provided provisional evidence for a new effect in the backward inhibition paradigm. Specifically, performance is facilitated in trials *following* n–2 repetitions, relative to trials following n–2 switches.

Note that the effect is about the same size as the standard n–2 repetition cost. Hence, if n–3 is not controlled in a backward inhibition paradigm, this could significantly affect the size of n–2 repetition costs obtained. For instance, in Grange and Houghton’s (2010) experiments, performance in ACB*A* trials (which are usually classified as CB*A* trials) was about the same as performance in BAB*A* trials (which are usually classified as AB*A* trials), resulting in zero n–2 repetition costs if only these two sequence types are compared.

To check for the generality of the new finding, we aimed to replicate it with a different task switching paradigm. In Grange and Houghton’s (2010) paradigm, the tasks differ with respect to the stimulus dimension defining the target; hence, this paradigm requires attention switching. However, it does not require switching between competing stimulus–response rules. Rather, for all three tasks, participants have to press the key that is spatially compatible with the target (similar to Mayr & Keele’s, 2000, original paradigm). Many paradigms used in the task switching literature involve switching between competing stimulus–response rules, or category–response rules (Kiesel et al., 2010; Koch et al., 2010).

Hence we chose a paradigm with competing category–response mappings between the tasks to test the robustness of the new effect.

Experiment 1

In the following experiments, we used face categorisation tasks, which have been shown to produce reliable task switch costs (Schuch, Werheid, & Koch, 2012). In Experiment 1, participants switched between three tasks: categorising a facial photograph according to emotional expression (happy or angry), age (young or old), or sex (male or female). The participants used the same set of left and right response keys for all three tasks. This paradigm differs in a number of ways from the paradigm used by Grange and Houghton (2010): (a) arbitrary stimulus–response mappings were used rather than spatially compatible mappings as in Grange and Houghton; (b) tasks involved configural stimuli (faces) rather than perceptual properties of abstract shapes; (c) the tasks utilised multivalent responses (e.g., the left response key has different meanings, depending upon the currently relevant task; cf., Schuch & Koch, 2004); and (d) the tasks were more difficult, with mean RT being nearly twice as large (cf., Schuch, et al., 2012). Thus finding evidence for the new effect with such differing task demands would provide strong evidence as to the robustness and generality of the new effect.

Method

Participants. We planned to test 16 participants. Due to overbooking, data from 17 participants were collected (9 female, 8 male; mean age 30.8 years, SD 3.2, age range 25-40 years). All had normal or corrected-to-normal vision and were naïve with respect to the purpose of the experiment.

Apparatus & Stimuli. Standardized photographs of the faces of 40 different persons were presented (10 young male, 10 young female, 10 old male, 10 old female). Each person was photographed showing a happy or angry facial expression, resulting in 80 different pictures (see Schuch et al., 2012, for further details of the stimuli). Each picture was 10.6 cm by 14.1 cm in size, and was presented centrally on a computer screen, which was situated 50 cm in front of the participants.

Each portrait was presented inside a coloured frame, and frame colour indicated which task to perform. A yellow frame indicated the emotion task, a blue frame the sex task, a red frame the age task. Subjects used their left and right index fingers for responding. They responded by pressing one of two response keys on a German computer keyboard (the "Alt" and "Alt Gr" keys, which are located to the left and right of the space bar, respectively). For 9 of the 17 subjects, happy, young, and male faces were mapped to the left response key; angry, old, female, to the right. For the other 8 participants, the mapping was reversed (right for happy, young, male; left for angry, old, female).

Procedure. To familiarise themselves with the paradigm, participants started with a short practice session consisting of 12 trials in total (4 trials of each task, presented in pseudorandom order; immediate task repetitions could not occur). Then, participants proceeded with two blocks of 240 trials each, which were separated by a short break. In both blocks, cues and stimuli occurred in pseudorandom orders, with the following constraints. Each task occurred equally often in each block, immediate task repetitions were not allowed, and there was an equal number of n–2 task repetitions and n–2 switches in each block (i.e., 119 n–2 task repetition trials and 119 n–2 task switch trials; the first two trials per block could not be classified as either). Furthermore, each of the 80 stimuli occurred three times per block, and was presented once in the context of each of the three tasks. The person presented in a particular trial n was never the same as the persons presented in trials n–1 and n–2; person repetitions from trial n–3 to trial n occurred in 3.75% of the trials[4].

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[4] Removal of these trials did not alter the results in any way.

Every trial started with the presentation of a red, blue, or yellow frame for 500ms, followed by the presentation of a photograph inside the frame. Frame and picture stayed on the screen until the left or right response key was pressed. Then the screen turned black for 1,000ms. If the wrong key was pressed, an error feedback occurred after 500ms of blank screen and lasted for 1,000ms, after which the screen turned black again for another 500ms.

Design. The independent variables were *current n–2 repetition* (repetition vs. switch) and *previous n–2 repetition* (repetition vs. switch). The dependent variables were RTs and error rates.

Results

Data trimming proceeded as before (i.e., error trials were removed as well as the three trials following an error; additionally, the first three trials from each experimental block were removed; outliers were identified as RTs above 2.5 standard deviations of each participant's mean for each cell of the experimental design). The data from two participants were excluded due to very slow RT (mean RT was 1764ms and 1858ms for these two subjects, which was more than 2.5 standard deviations above the mean RT level of the other participants, 1127ms, SD 218ms).

The two-way ANOVA on RT data revealed a main effect of *current n–2 repetition*, $F(1,14) = 15.58$, MSe = 1797, $p<.01$, $\eta_p^2 =.53$, indicating standard n–2 repetition costs. Moreover, a main effect of *previous n–2 repetition* was obtained, $F(1,14) = 14.39$, MSe = 2316, $p<.01$, $\eta_p^2 =.51$, replicating the new effect first found in Grange and Houghton's (2010) data (see Figure 4). There was no significant interaction of *current* and *previous n–2 repetition*, $F(1,14)<1$. Post-hoc tests further investigating the new effect revealed that BAB*A* sequences were performed faster than CAB*A* sequences, 1124ms versus 1174ms, respectively, $t(14) = 2.89$, $p<.01$, one-tailed, and BCB*A* sequences were performed faster than ACB*A* sequences, 1084ms versus 1127ms, respectively, $t(14) = 3.23$, $p<.01$, one-tailed. The corresponding two-way ANOVA on error data (see Table 3) did not reveal any significant effects, all *F*s<1.

Insert Figure 4 about here

Discussion

Using face categorisation tasks, we replicated the data pattern found with the perceptual identification tasks applied in Grange and Houghton (2010). Note that the paradigm differs substantially from Grange and Houghton’s (2010) paradigm: Not only did the tasks involve configural stimuli (faces) rather than perceptual properties of abstract shapes, but also were the stimulus–response mappings completely arbitrary (as opposed to spatially-compatible mappings as in Grange and Houghton) and the responses were multivalent, creating maximal interference. Due to all these differences, the tasks were considerably more difficult, with mean RT being nearly twice as large as in Grange and Houghton’s paradigm. Yet, a difference between trials following n–2 repetitions versus switches is obtained, with BAB*A* sequences being faster than CAB*A* sequences, and BCB*A* faster than ACB*A* task sequences, providing strong evidence as to the robustness and generality of this new effect.

As a next step, we aimed to address a potential confound in the condition of n–2 switches followed by n–2 switches. When switching between three different tasks, the sequences in this condition are of the type ACB*A*. Note that, other than the remaining sequences, these sequences involve an n–3 task repetition. One might argue that there is persisting inhibition of the previously abandoned task A, leading to slower RTs in these trials. In order to eliminate the potential influence of n–3 task repetitions, a task switching paradigm with at least four different tasks needs to be applied, such that ACB*A* sequences can be replaced by DCB*A* sequences. Therefore, building upon the paradigm used in Experiment 1, we introduced a fourth face categorisation task in Experiment 2. This would allow us to compare task sequences of the types DCB*A*, BCB*A*, CAB*A*, and BAB*A*.

Experiment 2

The same paradigm as in Experiment 1 was used, including the tasks of classifying emotional expression, age, or sex, of a perceived face. In addition, a fourth task was introduced, where participants had to judge the eye colour of the perceived face, which could be either dark (i.e., brown) or light (i.e., blue or green).

Method

Participants. Thirty-two new participants were tested (19 female, 13 male; mean age 25.2 years, SD 4.7, age range 19-40 years). All had normal or corrected-to-normal vision and were naïve with respect to the purpose of the experiment. As testing n–2 repetition costs in the context of a four-task paradigm is novel to the literature, we decided to double the sample size from Experiment 1 to boost power, as effect sizes involving four-tasks are currently unknown in this context.

Stimuli and Responses. Sixteen faces were selected from the dataset described in Experiment 1, such that there was one exemplar for each cell of the following matrix: eye colour (light/dark) x emotion (happy/angry) x age (young/old) x sex (female/male). The tasks were cued as before; the eye colour task was indicated by a green frame. The 16 possible response mappings were fully counterbalanced across participants. Everything else was the same as in Experiment 1.

Procedure. The experiment started with a short practice consisting of 16 trials in total (4 trials of each task, presented in pseudorandom order, immediate task repetitions could not occur). Participants then completed eight blocks of 64 trials each, separated by short breaks. Four different pseudo-random task sequences were used and occurred in the order 1-2-3-4-4-3-2-1. Across the eight blocks, there was an almost equal number of DCB*A*, BCB*A*, CAB*A*, and BAB*A* sequences; frequencies were 120, 124, 122, 122, respectively, resulting in 488 trials in total. (The first three trials per block could not be classified as either sequence type and were not included in the analysis.) Within each block, each sequence type occurred at least 12 times and at most 18 times. ACBA sequences and direct task repetitions were not allowed. The same face could not be repeated within the next three trials. Each of the 16 stimuli occurred four times per block, once in the context of each task. Everything else was the same as in Experiment 1.

Design. The independent variables were *current n–2 repetition* (repetition [CAB*A*, BAB*A*] vs. switch [DCB*A*, BCB*A*]) and *previous n–2 repetition* (repetition [BAB*A*, BCB*A*] vs. switch [DCB*A*, CAB*A*]). The dependent variables were RTs and error rates.

Results

Data trimming proceeded as before. Two participants were excluded from analysis because of very slow RTs (mean RT levels [2212ms, 2272ms] more than 2.5 standard deviations above the mean RT level of all other participants [1089ms, SD 207ms]).

The two-way ANOVA on RT data (see Figure 5) revealed a main effect of *current n–2 repetition*, $F(1,29) = 17.63$, MSe = 4816, $p<.01$, $\eta_p^2 =.38$, indicating the standard n–2 repetition costs with slower mean RT in n–2 repetitions (1094ms) than switches (1041ms). Importantly, there was also a main effect of *previous n–2 repetition*, $F(1,29) = 6.73$, MSe = 2263, $p<.02$, $\eta_p^2 =.19$, indicating faster mean RT in trials following n–2 repetitions (1057ms) than trials following n-2 switches (1079ms). The interaction of *current* and *previous n–2 repetition* was not significant, $F(1,29)<1$.

Post-hoc tests further investigating the main effect of *previous n–2 repetition* revealed that BCB*A* sequences were performed significantly faster than DCB*A* sequences [$t(29) = 2.57$, *p*<.01, one-tailed]. There was a trend for BAB*A* sequences being performed faster than CAB*A* sequences [*t*(29) = 1.27, *p*=.10, one-tailed].[5]

Insert Figure 5 about here

The corresponding two-way ANOVA on error data (see Table 3) did not reveal significant effects. There was a trend for a main effect of *current n–2 repetition*, *F*(1,29)=3.00, *p*=.09, η_p^2 =.09, indicating higher error rate in n-2 repetitions (3.4%) than switches (3.0%). There was no main effect of *previous n–2 repetition* (*F*<1), and no interaction, *F*(1,29)=1.13.

Insert Table 3 about here

Discussion

Using four instead of three tasks, we confirmed the new task sequence effect: Performance was facilitated in trials following n–2 repetitions, relative to trials following n–2 switches. Unlike Experiment 1, n–3 task repetitions could not occur in Experiment 2, ruling out any potential influence of persisting task inhibition from n–3. Rather, using DCBA instead of ACBA task sequences, we found the same data pattern as before: Performance was better in trials following n–2 repetitions (BAB*A*, BCB*A*) than in trials following n–2 switches (CAB*A*, DCB*A*).

General Discussion

In this paper, we have provided initial evidence for a new sequential effect in task switching designs. By taking n–3 into consideration, we have shown that n–2 repetitions lead to improved performance in the *next* trial. That is, task sequences of the type BAB*A* are performed faster than CAB*A* sequences; likewise, BCB*A* sequences are performed faster than ACB*A* or DCB*A* sequences. This effect appears to be very robust and replicable (see meta-

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[5] The BAB*A*-CAB*A* difference was not significant due to one participant showing a large effect of 277ms in the opposite direction. If this participant is excluded from analysis, the difference between BAB*A* sequences and CAB*A* sequences is significant (*t*(28) = 2.26, *p*<.02, one-tailed) with BAB*A* sequences being faster than CAB*A* sequences (1074ms versus 1106ms respectively.)

analyses in Figures 1–2) and generalises across different task switching designs (cf. re-analysis of Grange & Houghton, 2010, with Experiments 1 and 2 of the current paper).

Practical Implications

This effect is important to take note of, as both BAB*A* sequences and CAB*A* sequences are n–2 task repetitions in the traditional sense (i.e., AB*A* sequences), and are thus usually not separated in analysis. Likewise, both BCB*A* sequences and ACB*A* sequences are n–2 task switches in the traditional sense (i.e., CB*A* sequences), and are usually not analysed separately. Yet, the current paper has shown reliable quantitative differences between these types of sequences. It thus seems pertinent for researchers in the future to control for n–3 when designing and analysing task switching experiments. Failure to balance the proportions of BAB*A* versus CAB*A* sequences, and BCB*A* versus ACB*A* sequences, can seriously distort the measurement of n–2 repetition costs.

Theoretical Implications

As well as providing an important note for future task switching designs, the present data raises important questions for theories of sequential effects in task switching. Specifically, why is there facilitated performance on the current trial if the previous trial was an n–2 repetition versus n–2 switch? This finding cannot be explained by current theoretical accounts of n–2 repetition costs. We would like to propose that this effect reflects trial-to-trial adaptation of cognitive control. Specifically, the detection of task conflict in n–2 repetitions leads to increased cognitive control in the following trial. That is, we suggest to think of n–2 repetitions as “task conflict” trials, as the currently-relevant task is in an inhibited state relative to the other—irrelevant—tasks. Thus, there is strong interference between competing tasks (i.e., high task conflict), and this interference needs to be overcome (i.e., task selection takes longer). As a consequence of the detected task conflict, more top-down control is recruited in the *next* trial, leading to stronger activation of the relevant task and/or stronger inhibition of irrelevant tasks in the next trial.

Such sequential adaptation of cognitive control has been reported extensively in the wider cognitive control literature. It was first described with respect to the detection of response conflict in response interference paradigms. For example, in the Eriksen flanker task, participants are required to respond to the direction a central arrow faces (either left or right). This arrow can be flanked by *congruent* arrows, which face in the same direction as the target (i.e., <<<<<), or it can be flanked by *incongruent* arrows, which face in the opposite direction (i.e., >><>>). RTs are thought to be slower for incongruent trials compared to congruent trials because there is interference between competing response alternatives (i.e., response conflict), and this interference needs to be overcome (i.e., response selection takes longer). However, Gratton, Coles and Donchin (1992) examined the effect of a previous trial's congruency on the current trial's performance. The effect of interest—the so-called Gratton effect—showed that responses to incongruent trials are speeded if the previous trial was also incongruent; similarly, RTs are faster to congruent trials if the previous trial was also congruent. To explain the Gratton effect, Botvinick et al. (2001) developed an influential modelling framework based on the idea of *conflict monitoring.* Specifically, whenever conflict is detected in the cognitive system—in the current example driven by incongruent stimuli—more top-down control is deployed in the *next* trial, leading to stronger activation of relevant stimulus features and/or stronger inhibition of irrelevant features, and hence, reduced response conflict.

Importantly, such trial-by-trial adjustments of cognitive control have also been demonstrated with other kinds of conflict. For instance, Jha and Kiyonaga (2010) demonstrated trial-by-trial modulation of cognitive control in a working memory task. In their paradigm, distractors that were either similar or non-similar to the to-be-remembered target were presented during the retention interval, inducing high versus low interference, respectively. The interference effect (i.e., the performance difference between trials with high versus low interference) was larger after trials with low interference than trials with high interference. Here, conflict did not occur on the level of responses, but on the level of information to be held in working memory. Nevertheless, conflict adaptation was found with higher interference control after trials with high than with low interference, mirroring the data pattern found with congruency effects. With respect to the effect reported in the present paper, two conclusions from Jha and Kiyonaga (2010) are noteworthy: (a) Increase in cognitive control might be triggered by cognitive conflicts other than response conflict; (b) the increase in cognitive control might encompass “(...) enhancement of all top-down mechanisms necessary to resolve conflict in the overall task set” (Jha & Kiyonaga, p. 1040).

As described above, we propose that task conflict is higher in n–2 repetitions than in n-2 switches. This is because the currently-relevant task is still inhibited in n-2 repetitions, and this inhibition is stronger than in n-2 switches. Thus, there is stronger interference between the competing tasks in n–2 repetitions. As a consequence of the detected task conflict, more top-down control is recruited in the *next* trial, leading to stronger activation of the relevant task and/or stronger inhibition of irrelevant tasks in the next trial.

Future Directions

An interesting question for further research would be to investigate the exact time course of this increase in top-down control. Possibly, increased top-down control facilitates task selection during the preparation interval (i.e., during the interval between task cue and imperative stimulus). Alternatively, facilitation of task selection might occur at the time of response selection (cf. Schuch & Koch, 2003).

Another question for future research concerns the interplay between the proposed adaptation to task conflict and the well-known adaptation to response conflict. We note, however, that response conflict is difficult to define in paradigms with three or more tasks, making it difficult to investigate this question within the present paradigm. Recently, Braverman and Meiran (2014) developed a task-switching paradigm with two tasks that allows to orthogonally manipulate task conflict and response conflict. This was done by presenting distractor stimuli that were associated with certain tasks or responses in a previous phase of the experiment. Applying such a methodology to investigate trial-to-trial adaptation of cognitive control on the level of both tasks and responses might provide a fruitful avenue for further research.

Conclusion

To conclude, we report a new sequential effect in task switching taking trial n–3 into consideration: Performance is facilitated in trials after n–2 task repetitions relative to trials after n–2 switches. We suggest this effect is driven by task-conflict-triggered increases in cognitive control. This new effect might provide important insights into cognitive control of conflict during task switching, and the role inhibition and task activation might play in resolving such conflict.

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Table 1. Factorial analyses of variance with the factors *current n–2 repetition* (repetition vs. switch) and *previous n–2 repetition* (repetition vs. switch) for all five conditions from Grange & Houghton (2010) reported in the mini meta-analysis. Significant effects (p<.05) are in bold.

Source	Current n–2 Repetition	Previous n–2 Repetition	Interaction
Experiment 1 (Standard Cues)	**F(1,31) = 6.40, MSe = 2487, p<.05, η_p^2 =.17**	**F(1,31) = 28.25, MSe = 2891, p<.001, η_p^2 =.48**	F(1,14) = 2.86, MSe = 5217, p=.10, η_p^2 =.08
Experiment 1 (Switched Cues)	**F(1,31) = 19.30, MSe = 3648, p<.001, η_p^2 =.38**	**F(1,31) = 25.60, MSe = 9236, p<.001, η_p^2 =.45**	F(1,31) = 0.22, MSe = 4131, p=.64, η_p^2 =.01
Experiment 2 (Abstract Cues)	**F(1,31) = 12.71, MSe = 3136, p<.05, η_p^2 =.29**	**F(1,31) = 28.24, MSe = 3250, p<.001, η_p^2 =.48**	F(1,31) = 1.42, MSe = 2747, p=.24, η_p^2 =.04
Experiment 3 (Standard Cues)	**F(1,31) = 19.28, MSe = 976, p<.001, η_p^2 =.38**	**F(1,31) = 18.82, MSe = 2596, p<.001, η_p^2 =.38**	F(1,31) = 1.82, MSe = 1041, p=.19, η_p^2 =.06
Experiment 3 (Standard Cues)	**F(1,31) = 5.81, MSe = 1671, p<.05, η_p^2 =.16**	**F(1,31) = 17.20, MSe = 4984, p<.001, η_p^2 =.36**	F(1,31) = 0.01, MSe = 1466, p=.94, η_p^2 =.00

Table 2. Descriptive statistics for the factorial re-analysis of the five conditions in Grange & Houghton (2010) reported in the mini meta-analysis.

Current trial:	n-2 switch		n-2 repetition	
Previous trial:	n-2 switch	n-2 repetition	n-2 switch	n-2 repetition
	ACBA	BCBA	CABA	BABA
Experiment 1 (Standard Cues)	744 (46)	672 (37)	745 (39)	716 (40)
Experiment 1 (Switched Cues)	767 (50)	676 (40)	809 (52)	728 (40)
Experiment 2 (Abstract Cues)	729 (31)	666 (30)	755 (35)	710 (31)
Experiment 3 (Standard Cues)	669 (35)	622 (32)	686 (36)	654 (35)
Experiment 3 (Switched Cues)	695 (35)	643 (26)	713 (35)	660 (29)

Table 3. Mean error rates in % (SD in parentheses) in Experiments 1 and 2, separately for current trial n–2 repetitions/switches and previous trial n–2 repetitions/switches.

Current trial:	n–2 switch		n–2 repetition	
Previous trial:	n–2 switch	n–2 repetition	n–2 switch	n–2 repetition
	ACBA or DCBA	BCBA	CABA	BABA
Experiment 1	2.3 (0.5)	2.3 (0.5)	2.6 (0.5)	2.3 (0.5)
Experiment 2	2.8 (0.4)	3.1 (0.4)	3.5 (0.5)	3.3 (0.5)

Figure 1.

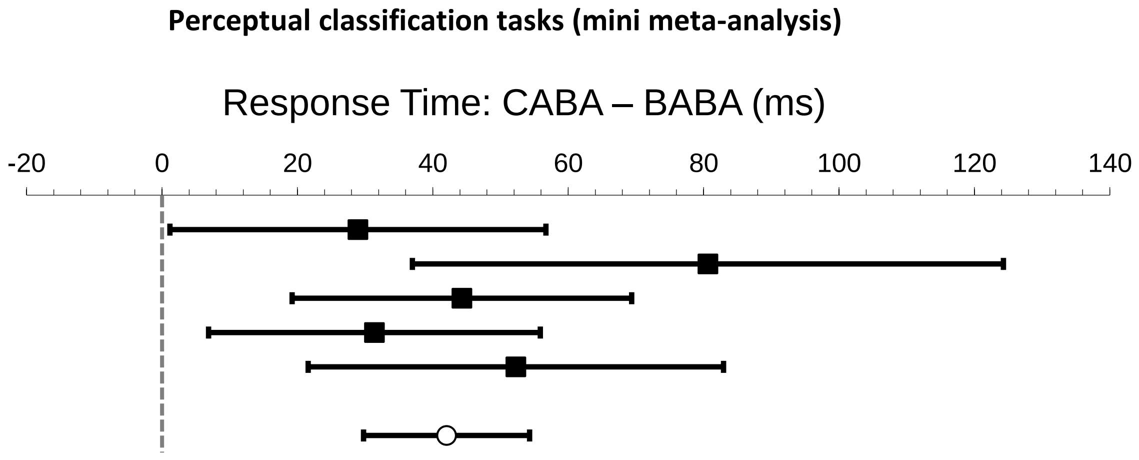

Figure 1. Mean difference—shown as a filled square—in response time (in milliseconds, ms) between CABA and BABA sequences for five experimental conditions from Grange and Houghton (2010). (From top-to-bottom): Exp.1, standard condition; Exp.1, switched condition; Exp.2, unrelated-cue condition; Exp.3, standard condition; Exp.3, switched condition. The open circle represents the estimate from the mini meta-analysis of the five studies using a mixed-effects model. The Error bars denote 95% confidence intervals around each mean.

Figure 2.

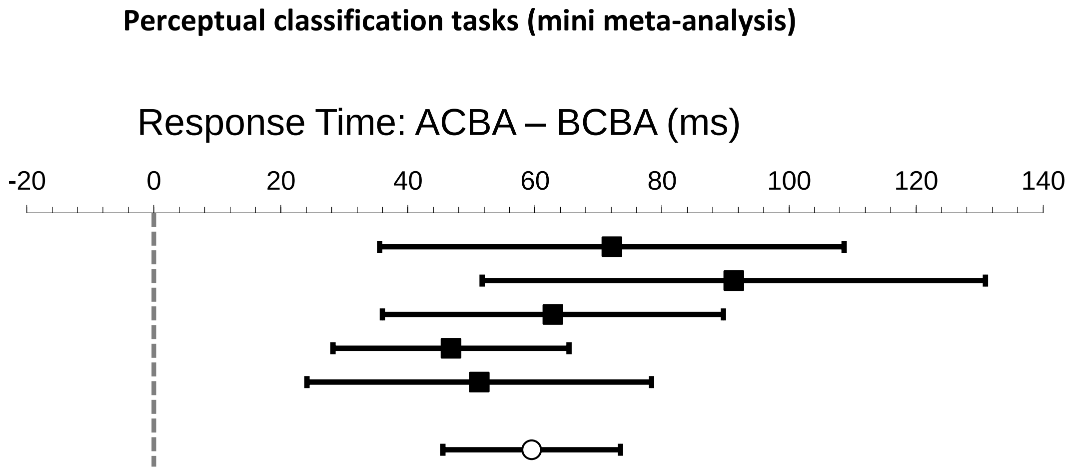

Figure 2. Mean difference—shown as a filled square—in response time (in milliseconds, ms) between ACBA and BCBA sequences for five experimental conditions from Grange and Houghton (2010). (From top-to-bottom): Exp.1, standard condition; Exp.1, switched condition; Exp.2, unrelated-cue condition; Exp.3, standard condition; Exp.3, switched condition. The open circle represents the estimate from the mini meta-analysis of the five studies using a mixed-effects model. The Error bars denote 95% confidence intervals around each mean.

Figure 3.

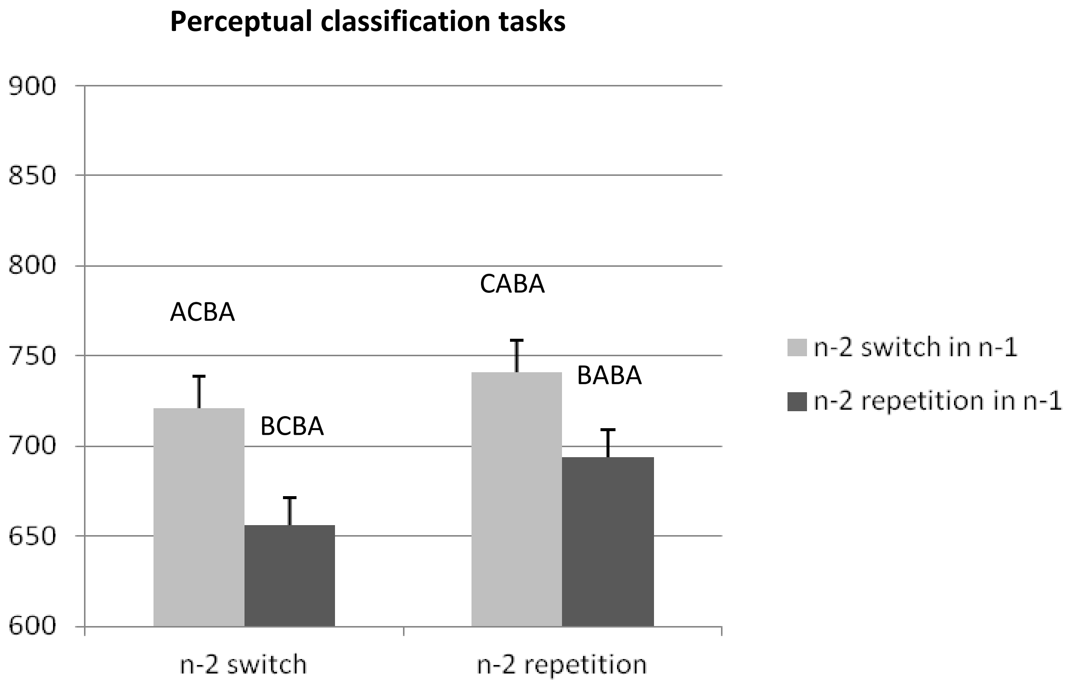

Figure 3. Factorial re-analysis of the five experimental conditions from Grange and Houghton (2010) that were included in the mini-meta-analysis. Mean reaction time (in milliseconds, ms) plotted as a function of n–2 repetition on the current trial and n–2 repetition on the previous trial. Error bars denote +/- 1 standard error around each mean. BABA = task sequence with two consecutive n–2 repetitions; CABA = n–2 repetition preceded by n–2 switch; BCBA = n–2 switch preceded by n–2 repetition; ACBA = two consecutive n–2 switches.

Figure 4.

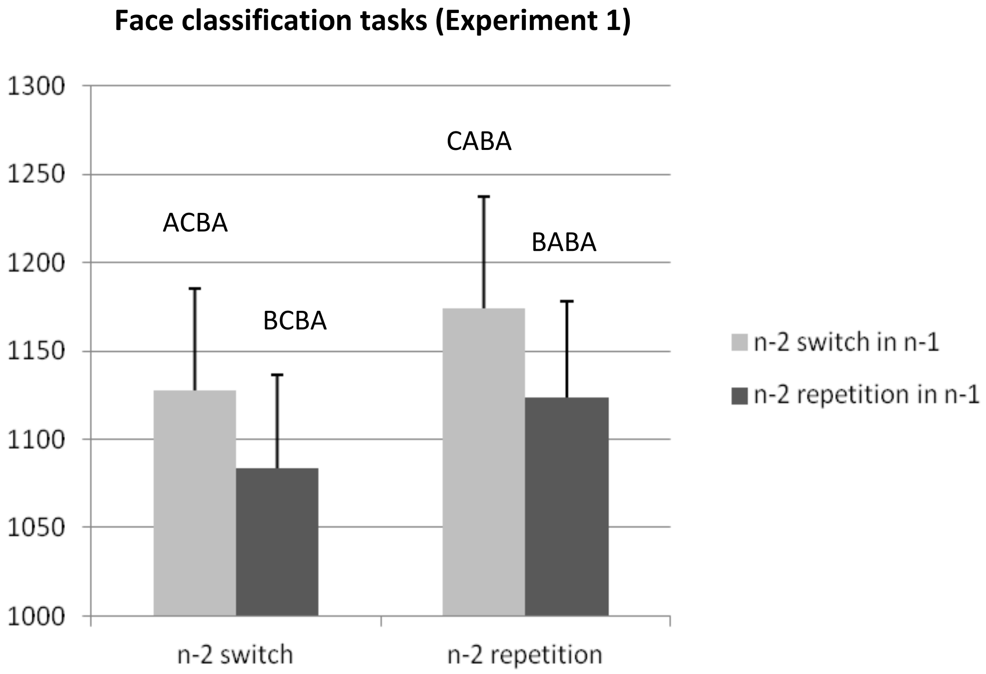

Figure 4. Experiment 1 (switching between classification of emotional expression, age, and sex of a perceived face). Mean reaction time (in milliseconds, ms) plotted as a function of n–2 repetition on the current trial and n–2 repetition on the previous trial. Error bars denote +/- 1 standard error around each mean. BABA = task sequence with two consecutive n–2 repetitions; CABA = n–2 repetition preceded by n–2 switch; BCBA = n–2 switch preceded by n–2 repetition; ACBA = two consecutive n–2 switches.

Figure 5.

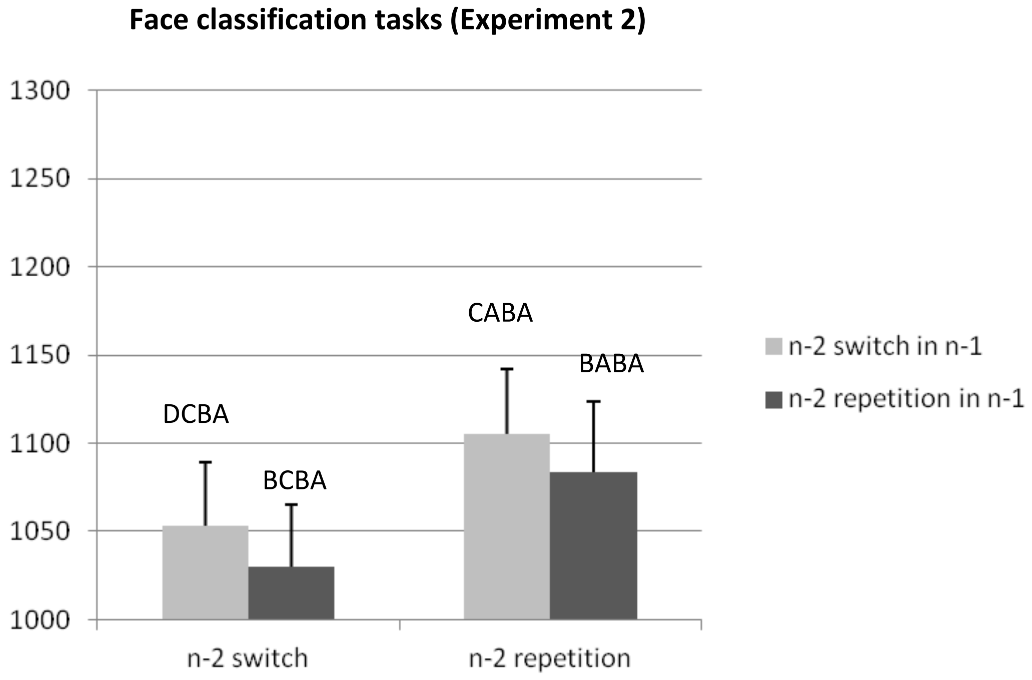

Figure 5. Experiment 2 (switching between classification of eye gaze, emotional expression, age, and sex of a perceived face). Mean reaction time (in milliseconds, ms) plotted as a function of n–2 task repetition on the current trial and n–2 task repetition on the previous trial. Error bars denote +/- 1 standard error around each mean. BABA = task sequence with two consecutive n–2 repetitions; CABA = n–2 repetition preceded by n–2 switch; BCBA = n–2 switch preceded by n–2 repetition; DCBA = two consecutive n–2 switches.