

Does incidental sequence learning allow us to better manage upcoming conflicting events?

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Authors' note: The datasets generated during the current study are available in the Open

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Abstract

Recent proposals emphasize the role of learning in empirical markers of conflict adaptation. Some of these proposals are rooted in the assumption that contingency learning works not only on stimulus-response events but also on covert processes such as selective attention. In the present study we explored how these learning processes may apply to trial-to-trial modulations of selective attention, mirroring the sequential nature of congruency sequence effects. Two groups of participants performed a four-choice Stroop task in which the color to which they responded on each trial acted as a probabilistic predictor either of the external response to be emitted on the next trial, or the congruency level (and therefore control demands) on the next trial. The results showed clear effects of sequence learning for external responses, but no evidence of learning about sequential stimulus-conflict associations. The implications of these results are discussed in relation to other learning-based phenomena of conflict adaptation, and suggest that learning of stimulus-control associations are strongly constrained by event boundaries.

Conflict adaptation

Across all levels of information processing, cognitive agents can be exposed to interference that jeopardizes goal-directed selection processes. In the lab such interference can be studied using so-called conflict tasks. For example, in the classic Stroop task (MacLeod, 1992; Stroop, 1935) responding to the color in which a word is presented (i.e., the goal) can suffer interference from the meaning of that word when it refers to a different color (e.g., “RED” printed in blue), because word reading occurs automatically. This interference can be reliably captured in performance measures, as people are often slower and/or less accurate on such incompatible color-word pairings as compared to cases in which color and meaning are compatible (i.e., “RED” printed in red). This performance difference is referred to as the congruency effect.

In order to achieve goal-directed behavior in the face of interference, the brain is believed to be equipped with various cognitive control processes. One such process has been referred to as conflict adaptation, which concerns the brain’s ability to swiftly adjust attentional settings when interference or ‘conflict’ is detected in order to cope well with current and/or future task demands. Various empirical markers of conflict adaptation can be derived from exploring the congruency effect. For instance, the congruency effect is typically smaller right after having responded to a conflict trial (i.e., the congruency sequence effect or CSE; Gratton, Coles, & Donchin, 1992); or after having experienced a disproportionately large amount of conflict trials for a given block (i.e., List Wide Proportion Congruency effect or LWPCE; Logan & Zbrodoff, 1979), a specific context (Context Specific Proportion Congruency effect or CSPCE; Crump, Gong, & Milliken, 2006), or a specific item (Item Specific Proportion Congruency effect or ISPCE; Jacoby, Lindsay, & Hessels, 2003). In all cases, the idea is that conflict detection (occurring mainly on incongruent trials) results in a

more appropriate balance of attentional focus between relevant and irrelevant information such that potential upcoming conflicts can be better managed (but see Schmidt, 2018).

Classical models of cognitive control described well the dynamic processes that are required for managing conflict events and maintaining goal-directed behavior (Norman & Shallice, 1986). Yet, they often failed to specify how the brain 'decides' when and how to adjust control settings. This left these accounts plagued by homunculi rather than providing a mechanistic understanding of conflict adaptation (Abrahamse, Braem, Notebaert, & Verguts, 2016; Verbruggen, McLaren, & Chambers, 2014; Verguts & Notebaert, 2009). A more mechanistic approach followed on the basis of computational work, with the seminal work by Botvinick, Braver, Barch, Carter, & Cohen, (2001) setting the stage. Botvinick et al. proposed the conflict monitoring theory (CMT), in which internally generated conflict signals served as the cues for the moment at which increased control is required. Even though this satisfies the requirement of knowing *when* to adjust control, a fully mechanistic account also has to outline *how* to adjust control. One candidate 'how' proposal is outlined below, and builds on learning as the main driver of conflict adaptation.

Learning-based conflict adaptation

For long, and (still) for many, learning has been understood as the cognitive complement of control. Cognitive agents go through life building habits, and recruit control processes when these habits violate current goals. The extreme case of such logic is the currently ongoing debate on the extent to which conflict adaptation markers (i.e., CSE, LWPCE, ISPCE, CSPCE) can be 'explained away' by learning and memory processes (for reviews see Schmidt, 2013, 2018). A related but potentially more synergetic approach is to understand conflict adaptation as evolving itself from learning processes (Egner, 2014, 2017, Verguts & Notebaert, 2008, 2009). Verguts and Notebaert, for example, proposed a computational model in which conflict serves as a teaching signal to drive adaptation: Upon conflict

detection, all currently active representations are (further) strengthened, and because active representations are typically task-relevant, this results in increased control. This principle about how the brain knows how to adjust control settings, was shown to generate both CSEs and ISCPEs. Recently, Abrahamse et al. (2016) elaborated on this learning-based approach on conflict adaptation (see also Egner, 2014), and argued that this approach can explain why conflict adaptation – like has been long known for learning – is sensitive to context and reward, and not critically dependent on awareness and expectations (e.g. Jiménez & Méndez, 2013; Jiménez & Méndez, 2014).

In general, the computational and conceptual work outlined above builds on two critical assumptions. First, it builds on the insight that the brain processes in analogous ways both internally and externally generated events (e.g., conflict signals and physical stimuli), and operates similarly via covert and overt actions (e.g., attentional adjustments and motor actions). Indeed, just like external stimuli can bias overt actions (e.g., in classical conditioning, contingency learning, or sequential event learning), the CMT as well as its extended work by others (e.g., Verguts & Notebaert, 2008; 2009) implies that internally generated conflict signals can bias covert actions such as attentional focus. A second, related insight is that core principles from associative learning can be applied to critical instances of ‘selection’ inside the cognitive agent (i.e., hidden states in information processing). An early example of this insight is the working memory gating model by Frank, Loughry and O’Reilly (2001), in which reinforcement learning shapes input and output selection in working memory. In the current context, this reasoning can be extended to the selection of contextually optimal attentional parameters to produce conflict adaptation. For example, in the model by Verguts and Notebaert (2008; 2009) Hebbian learning is at work not only for active stimulus and/or response representations, but also for active task representations – and this drives conflict adaptation.

The current study

The above mentioned LWPC, CSPC and ISPC effects are three empirical demonstrations in support of a critical role of associative learning in conflict adaptation, as trial history provides contingencies that can be learned to drive adaptation (but see Schmidt, 2018). Yet, a learning-based account of conflict adaptation postulates that associative learning is its main engine overall. As such, it is important to also explore associative learning processes that mirror the time course of the congruency sequence effect – one of the main empirical markers of conflict adaptation – in terms of adaptation occurring not only within trials (e.g., (Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011) but also across successive trials. In tackling this issue, here we take inspiration from the sequence learning literature.

In the sequence learning literature, it has been shown that the brain can learn about sequential regularities between successive stimulus-response events without being instructed to do so (i.e., incidental learning). For example, in their seminal paper, Nissen and Bullemer, (1987) introduced the serial reaction time (SRT) task, in which participants are required to generate spatially compatible responses to spatially defined stimuli on the screen. When these S-R events were presented in a fixed, repeating sequence, participants' performance improved with practice up to the moment that the sequence was replaced by random series of events that caused performance to drop substantially. This indicates that participants were able to better anticipate the upcoming (external) S-R event by using information from the previous (external) S-R event (e.g., stimulus-stimulus, response-response, or stimulus-response learning; see Abrahamse, Jiménez, Verwey, and Clegg, 2010). For example, sequential learning at the level of stimulus-stimulus contingencies (i.e., perceptual sequence learning) has been shown in studies that decoupled the sequence to be learned from response features (e.g. Deroost & Soetens, 2006; Howard, Mutter, & Howard, 1992; Mayr, 1996; Remillard, 2003; Song, Howard, & Howard, 2008), and even in studies that arranged two

independent sequences involving both perceptual and motor features (D'Angelo, Jiménez, Milliken, & Lupiáñez, 2013; Mayr, 1996). Moreover, studies have shown that sequential S-R learning arises even under probabilistic conditions, where the sequential trials are continuously intermixed with unpredictable trials (Jiménez, Lupiáñez, & Vaquero, 2009; Shanks, Wilkinson, & Channon, 2003), and – interestingly for current purposes – even when the sequence is implemented in the context of interference tasks (Deroost, Vandebossche, Zeischka, Coomans, & Soetens, 2012; Koch, 2007).

As mentioned, learning-based conflict adaptation builds on the notions that the brain operates in similar ways on internal and external stimuli, on overt and covert actions, and on the formation of associations between them. Thus the question arises on whether participants can learn to associate external stimulus-response information from the current trial to internally computed conflict events (or the corresponding attentional adjustments) on the following trial. Previous studies have shown that people can improve performance based on explicit congruency-level cues presented before each trial, which predict the amount of conflict presented on the upcoming trial (Bugg & Smallwood, 2016; Ghinescu, Schachtman, Stadler, Fabiani, & Gratton, 2010; Gratton et al., 1992; Logan & Zbrodoff, 1979). Following this observation, we here hypothesize that the brain can also learn to anticipate the congruency level of the next trial based on predictive information conveyed by an uninstructed, incidental predictor presented on the preceding trial, such as the stimulus feature to which they are responding on this preceding trial. As such, the current study provides for an empirical test of core assumptions of learning-based control.

We tested two groups of participants. A first group performed a relatively simple, but probabilistic, SRT task, in which the color and response of the previous trial acted as valid predictors (80% valid) of the color and response on the current trial. A second group performed the same task in a very similar design but with one crucial change: here, the color

and response of the previous trial were valid predictors (80% valid) not of the color and response but rather of the congruency level (congruent or incongruent) of the current trial – with congruency level thus being an approximation of the presence/absence of conflict and the need of attentional adjustments. Whereas we expected to find clear learning (through improvements in performance) for the first group in replication of previous SRT studies (e.g., Deroost et al , 2012; Koch, 2007), the critical question was whether the second group could also learn the between-trials contingencies in order to better manage upcoming conflict.

Experiment

Two independent groups of participants performed a 4-choice manual Stroop task over a series of six blocks of trials. Unknown to the participants, the succession of trials was structured in a different way for each of these two groups. In the external (color→color) condition, the color on each trial, and therefore the response required on that trial, conveyed 80% valid information about the color and response required on the following trial. In the internal (color→congruency) condition, the same attributes of each trial contained 80% valid information about the amount of conflict to be encountered on the following trial, and therefore on the optimal attentional settings required to respond to that trial.

Method

Participants. The experiment was conducted in accordance with Spanish regulations, and with the ethical standards of the 1964 Declaration of Helsinki. Forty-eight students (6 male, mean age 21, ranged between 18 and 40) from the University of Santiago de Compostela signed an informed consent to participate in the experiment in exchange for a monetary fee or academic credit, and half of them were randomly assigned to either the color→color or color→congruency condition.

Apparatus and stimuli. The experiment was designed and controlled using INQUISIT 4 (Inquisit 4, 2015) software, running on personal computers connected to 22-in monitors, with a resolution of 1920×1080 . Participants viewed the monitors from an unrestricted distance of approximately 60 cm, and responded on a standard QWERTY keyboard placed in front of them. On each trial, participants saw a word, randomly selected from the Spanish words referring to the colors red ("rojo"), blue ("azul"), green ("verde"), and yellow ("amarillo"), printed in Arial, lower case, 32 points font, colored either in a congruent or in an incongruent color, and presented against a grey background. Participants were asked to respond to the color in which the word was written using the keys corresponding to the letters 'z', 'x', 'n', and 'm' to respond, respectively, to the colors red, green, blue and yellow. The response keys were marked with appropriate colored stickers.

Procedure. Participants received initial instructions informing them that they should rest their index and middle fingers from each hand on the response keys, and that their task consisted of responding as fast and accurately as possible by pressing on the key corresponding to the color in which the current word was written. In a first, practice block, participants were given the opportunity to learn about the color-key mapping, by responding to 50 trials in which the word stimuli were not related to the colors. In this part of the task, the color-to-response-location mapping was facilitated by locating four color labels ("rojo", "verde", "azul", "amarillo") at the bottom of the screen, marking the relative location of the response keys. After the practice block, the word labels were removed, and the experiment proceeded to the six experimental blocks.

Each experimental block consisted of 96 Stroop trials, in which the meaning of the words corresponded to one of the four possible colors, with a congruency rate of .50. The succession of trials was structured so that, in the external, (color→color) condition, each color predicted the next color with a validity of .80. In the internal, (color→congruency)

condition, each color predicted the congruency level of the next trial with the same validity. To control for the potential influence of particular predictor-target pairs, in the external condition the color→color contingencies were counterbalanced over modules of six participants, so that every predictor-target pair was equally represented (e.g., the sequences red→green, red→blue, and red→yellow corresponded to frequent sequences for exactly two participants out of each module of six). For the internal condition, the color→congruency contingencies were also counterbalanced in a similar way so that, over a module of six participants, every possible pair of colors was associated once with a congruent successor and once with an incongruent successor. Table 1 illustrates this counterbalanced design.

Table 1. Assignment of predictive values to each possible color predictor, counterbalanced for participants, in both the color→congruency and color→color conditions.

| Condition Participants | Predictor | | | | | | | |
|---------------------------|----------------------|-----------------|----------------------|-----------------|----------------------|-----------------|----------------------|-----------------|
| | Red | | Green | | Blue | | Yellow | |
| | color→ congruency | color→ color | color→ congruency | color→ color | color→ congruency | color→ color | color→ congruency | color→ color |
| 1/7/13/19 | Congruent | Green | Congruent | Blue | Incongruent | Yellow | Incongruent | Red |
| 2/8/14/20 | Incongruent | Green | Incongruent | Yellow | Congruent | Red | Congruent | Blue |
| 3/9/15/21 | Congruent | Blue | Incongruent | Yellow | Incongruent | Green | Congruent | Red |
| 4/10/16/22 | Incongruent | Blue | Congruent | Red | Congruent | Yellow | Incongruent | Green |
| 5/11/17/23 | Congruent | Yellow | Incongruent | Blue | Congruent | Red | Incongruent | Green |
| 6/12/18/24 | Incongruent | Yellow | Congruent | Red | Incongruent | Green | Congruent | Blue |

As for the invalid trials, they were introduced continuously among the valid trials, in a proportion of .20. The inclusion of invalid trials fulfilled the simultaneous goals of masking the sequential contingencies, and allowing for a continuous test of sequence learning. In the color→color condition, we also precluded immediate repetitions (e.g., red-red) and alternations (red-green-red) from the control trials, because neither can appear in valid trials, and these patterns are known to produce particular effects independent of learning (cf. Vaquero, Jiménez, & Lupiáñez, 2006). Thus, whenever an invalid trial was scheduled by the program, the valid trial that would have followed based on the sequence was replaced by the only remaining candidate that did not produce either a repeating or an alternating pattern.

For instance, if valid successor after the series red-green was blue, but the latter stimulus was to be replaced by an invalid trial, then a yellow stimulus would replace the planned blue trial. In principle, for the color→congruency condition the same precaution was not needed to make valid and invalid trials comparable, because alternations and repetitions could arise equally in both valid and invalid trials. Yet, in order to make both conditions more comparable, we also implemented these restrictions over the color→congruency group, thus precluding immediate repetitions and alternations from appearing in the series.

Each trial started with a fixation cross presented at the center of the screen, that was replaced after 500 ms by an empty screen. After 250 ms, the blank screen was followed by the target, which remained on screen until the participant issued a response. If the response was correct, the next trial came immediately, thus producing a response-to-stimulus interval of 750 ms. When an error was committed, participants heard a tone, and the screen remained blank for an additional interval of 1000 ms, before proceeding to the following trial. After a training block, participants were informed about the average reaction time and the percentage of correct responses produced on that block, and they were asked to keep responding as fast as possible, while maintaining the proportion of errors below .10. At the end of the sixth experimental block, participants completed a questionnaire that assessed their knowledge about the underlying regularities. In the color→color condition, participants were asked to select the most likely successor that they expected after a trial displaying each of the four colors. They could choose either one of the four successors, or a fifth alternative that stated that "any one" was possible. In addition, they were allowed to use a Likert Scale marked from 0 to 10 to rate their confidence on each response. In the color→congruency condition participants were asked to select whether, after each possible color, they expected an "easy" (i.e., congruent) or a "difficult" (incongruent) successor, and they were also asked to rate their confidence through a similar Likert Scale.

Design. The experimental design included a between-participants variable *Group* (color→color vs. color→congruency prediction), and two main within-participants factors, *Congruency* (2, Congruent vs. Incongruent trials) and *Predictability* (2, Valid vs. Invalid trials). Because learning to exploit the sequential regularities might take time, we also included *Practice* as an additional within-participants variable, collapsing the training blocks into two practice halves. Two Analyses of Variance (ANOVAs) were conducted separately using reaction times (RTs) and percentage of errors as the dependent variables. RTs were our main focus, but we analyzed errors for completeness, and to confirm that any effect observed in RTs could not be attributed to a trade-off between speed and accuracy.

Results

Reaction Times. The first trial of each block was removed from the analyses (since they were not predicted by any previous trial), as well as the latencies from incorrect responses, from the trial immediately following an error (Notebaert, Gevers, Verbruggen, & Liefvooghe, 2006), and from those trials producing RTs straying more than 3 standard deviations from the mean, computed for each block and participant separately. The omnibus ANOVA conducted on RTs did not show a significant effect of Group, $F(1,46)=0.75$, $p=.39$; $\eta_p^2=.02$, but it produced significant main effects of Congruency (642 vs. 721 ms), $F(1,46)=76.06$, $p<.0001$; $\eta_p^2=.62$, Predictability (663 vs. 701 ms), $F(1,46)=15.59$, $p<.0001$; $\eta_p^2=.25$, and Practice (697 vs. 667 ms), $F(1,46)=10.36$, $p=.002$; $\eta_p^2=.18$. The Congruency \times Group interaction was not significant, $F(1,46)=0.01$, $p=.98$; $\eta_p^2<.001$ but, importantly for our theoretical purposes, there was a significant Predictability \times Group interaction, $F(1,46)=13.24$, $p=.001$; $\eta_p^2=.22$ which showed that learning differed between both groups. An inspection of Figures 1a and 1b showed that learning arose clearly in the color→color group for both congruent and incongruent trials, but that this was not the case in the color→congruency group.

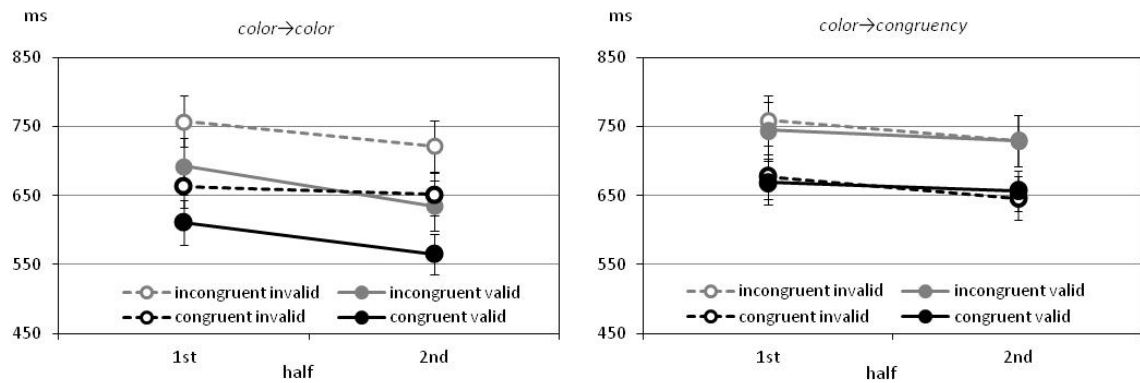


Figure 1. Mean reaction times as a function of Practice (first vs. second training half), represented separately for congruent and incongruent trials, and for valid and invalidly predicted trials. Left panel represents the results obtained for participants assigned to the color→color Group, and right panel represents the results obtained for participants in the color→congruency Group.

To assess more specifically the effects of Predictability separately for each group, we conducted an independent ANOVA for each group. The analysis conducted for the color→color group showed a clear effect of Predictability (the average RTs were 626 vs. 698 ms, respectively for valid and invalid trials), $F(1,23)=15.41$, $p=.001$; $\eta_p^2=.40$, which did not interact with Congruency, $F(1,23)=0.18$, $p=.67$; $\eta_p^2=.01$. The Predictability \times Practice interaction did not reach significance, $F(1,23)=3.49$, $p=.07$; $\eta_p^2=.13$, although it showed a numerical increase of the effect of predictability with practice from 52 to 86 ms. The three-way Congruency \times Predictability \times Practice interaction did not reach significance either, $F(1,23)=.16$, $p=.69$; $\eta_p^2=.01$. A Bayesian analysis conducted using JASP with default priors (JASP Team, 2018), to compute the relative plausibility of obtaining these data given H1 (participants' responses discriminated between valid and invalid trials) relative to H0, produced a $BF_{10}=1.31 \times 10^{+5}$, thus showing that the data clearly supported H1.

For the color→congruency group, the analysis showed no evidence of learning, as the effect of Predictability was not significant for this group (700 vs. 703 ms), $F(1,23)=0.36$, $p=.55$; $\eta_p^2=.02$. A Bayesian analysis analogous to that conducted for the color→color Group, produced a $BF_{10}=0.16$ (or a $BF_{01}=6.36$) thus suggesting that the data supported H0 for this group. Neither the two-way Predictability \times Congruency, $F(1,23)=0.19$, $p=.66$; $\eta_p^2<.01$, and

Predictability \times Practice interactions, $F(1,23)=1.32$ $p=.26$; $\eta_p^2=.05$, nor the three-way Predictability \times Practice \times Congruency interaction $F(1,23)=0.06$, $p=.80$; $\eta_p^2<.01$, reached significant levels in the analysis.

Accuracy. The accuracy levels were generally high, and close to ceiling (.96). The ANOVA conducted on the percentage of correct responses showed a significant main effect of Group, $F(1,46)=4.75$, $p=.04$; $\eta_p^2=.09$, indicating that performance was slightly more accurate in the color \rightarrow congruency group (.966 vs. .950). The effect of Congruency just missed significance in the analysis (.961 vs. .954), $F(1,46)=3.36$, $p=.07$; $\eta_p^2=.07$, and the effect of Practice was also non-significant, $F(1,46)=0.5$, $p=.48$; $\eta_p^2=.01$, but there was a significant effect of Predictability (.969 vs. .947), $F(1,46)=25.47$, $p<.0001$; $\eta_p^2=.36$, that indicated that learning was observed in this measure. Most importantly for the present purposes, the Group \times Predictability interaction was also significant, $F(1,46)=15.77$, $p<.001$; $\eta_p^2=.255$, showing that the effect of Predictability was different in the color \rightarrow color (.970 vs. .929) as compared to the color \rightarrow congruency group (.969 vs. .964). To better understand this interaction, independent analyses were conducted for each of these two groups, focusing on the effects and interactions involving Predictability.

The ANOVA conducted on the color \rightarrow color group showed a significant effect of Predictability $F(1,23)=24.21$, $p<.001$; $\eta_p^2=.51$, $BF_{10}=1.62 \times 10^{+8}$. The effect of Predictability did not interact with either Congruency, $F(1,23)=0.36$, $p=.55$; $\eta_p^2=.01$, but there was a non-significant trend to produce a larger effect of Predictability with Practice (.032 vs. .049 points of difference, $F(1,23)=3.79$, $p=.06$; $\eta_p^2=.14$).

As for the ANOVA conducted on the color \rightarrow congruency group, in this case neither the main effect of Predictability $F(1,23)=1.79$, $p=.19$; $\eta_p^2=.07$, nor any of the interactions involving this factor reached significant effects. The Bayesian analysis produced a $BF_{10}=0.34$ ($BF_{01}=2.96$), lending further support to H_0 . Thus, consistently with the results

observed in the measures of RT, the percentage of hits also showed learning selectively in the group that experienced external contingencies (i.e., color→color group) but not in the group exposed to internal contingencies (i.e., the color→congruency group).

Finally, to see whether participants in each of these conditions would be able to report the contingencies they were exposed to, we analyzed their responses to the post-task questionnaire. To obtain a single score that represents the amount of knowledge directly expressed through this questionnaire, we scored their responses with 1 or -1 in terms of whether the successor of each color was either correct or incorrect (a score of 0 was entered when a participant used the "any one" alternative), and multiplied that score by the confidence rate deposited on that response according to the Likert scale. These average scores differed significantly between groups, $t(46)=2.25$, $p=.03$ (two-tailed). Independent T tests indicated that the average score obtained by the color→color group (2.02) was significantly different from 0, $t(23)=2.34$, $p=.03$, whereas the corresponding score obtained by the color→congruency group (-0.14) was not different from 0, $t(23)=-.33$, $p=.75$.

Discussion

The present study investigated whether participants can use information provided by the previous trial not only to predict the (color-response) identity of the following trial, but also to get prepared for an increased or decreased likelihood to experience conflict on that trial. Our results replicate the standard observation that participants can learn to use sequential contingencies established between successive colors, as demonstrated by faster responses and a reduced amount of errors when responding to valid than to invalid trials in the color→color group. However, we found no evidence for our main hypothesis that the same should be observed for color→congruency contingencies. As the observations in both groups separately (as well as the comparison between them) allow for interesting additional discussion, we will now discuss each of those two contingency groups in turn.

Notably, while the color→color group did show learning, there was no interaction with practice. However, relatively fast learning has also been observed in other sequence learning studies involving only first-order probabilistic contingencies (D'Angelo et al., 2013).

Because the goal of learning in this case consists only of four pair-wise associations between each of the four possible colors and its more likely successor, and they are repeated about 20 times per block, it is not surprising that the learning was already well established during the first training half.

Interestingly, while we observed a clear benefit in performance of color-color contingencies, this benefit did not further interact with the congruency effect. This result contrasts with previous findings by Deroost and colleagues (2012), who showed a reduction of the Stroop effect on predictable trials. Our experiment differed from the study by Deroost and colleagues (2012) in that we assigned the four colors to four, instead of two, response buttons, and used restrictions in color sequences avoiding direct color repetitions from both the previous trial and the trial before that. Therefore, our restrictions might have excluded response repetition effects that can considerably reduce congruency effects (e.g., Mayr, Awh, & Laurey, 2003). More broadly, however, our results are consistent with previous findings by Koch (2001, 2005) who also found a clear benefit of predictable (task) sequences that did not further interact with the task switch cost. Although speculative at this point, these findings might suggest that sequential predictability is not effective for reducing interference effects at the task level.

In addition to showing that participants can learn about a sequence of colors in the context of a four-choice Stroop task, our main goal was to assess whether participants could also learn to use the same predictors to anticipate the amount of conflict expected for the following trial. Previous work has indicated a role for associative learning processes in conflict adaptation. For example, the CSPC and ISPC effects have been interpreted as

showing the formation of synchronic associations between contextual features (e.g., location, color, identity) and the amount of conflict encountered on that trial (Cañadas, Rodríguez-Bailón, Milliken, & Lupiáñez, 2013; Crump & Milliken, 2009). In extension of this work, we here explored the extent to which conflict-related representations can become associated to the imperative feature to which participants responded on the previous trial – i.e., whether they can learn a sequence that relates the previous color (and the response produced on that trial) to the level of conflict expected on the following trial. Effects of sequence learning have been demonstrated for perceptual-motor features between successive trials in a variety of settings (for a review, see Abrahamse et al., 2010), and here we again showed that this learning occurs in the context of a Stroop task when each color predicts the color of the following trial (cf. Deroost et al., 2012). Yet, despite the very similar design used in the color→congruency group, we observed no learning for contingencies between previous trial color and the congruency level on the next trial.

The absence of learning in the color→congruency group stands in contrast not only with the learning observed in the current study for a comparable color→color group, but also with learning-based modulations of control in previous work. First, as mentioned above, the CSPC (Crump et al., 2006) and ISPC effects (Jacoby et al., 2003) have been interpreted as showing that specific features of a trial can become associated with its control demands, and thus trigger the appropriate attentional adjustments. Second, pre-cueing studies suggest that cues interspersed between successive trials also become associated with the amount of conflict expected on the following trial, thus improving participants' responding to the expected conflict (Bugg & Smallwood, 2016; Ghinescu et al., 2010; Gratton et al., 1992; Logan & Zbrodoff, 1979). Interestingly, the interpretation of these phenomena in terms of learning-based conflict adaptation has been challenged by claims arguing, for instance, that pre-cueing effects could also be accounted for by a strategy where participants respond on

the basis of the distracters (Wühr & Kunde, 2008), and that ISPC and CSPC effects could arise from the learning of specific contingencies among items, contexts, and response features (Schmidt, 2013; 2018). However, there are a few studies that seem to be immune to these criticisms, showing that the CSPC effect can be observed even for new items not previously associated to congruency level contexts (Crump & Milliken, 2009), and that pre-cueing effects arise also in conditions that preclude the use of the strategy proposed by Wühr and Kunde (2008), as is the case in four-choice Stroop tasks (Bugg & Smallwood, 2016). Given these latter indications of learning-based conflict adaptation, the current observation that learning-based control does not arise in a sequential context, points to a possible boundary condition as to how and when associative learning steers conflict adaptation.

Specifically, Bugg and Smallwood's (2016) results showed evidence of pre-cueing effects (i.e., pre-cue based modulation of the congruency effect) in a four-choice Stroop task similar to that used in the current experiments, but in which the congruency level information was cued explicitly by the words "MATCHING" or "CONFLICTING", presented in the interval between successive trials. The present null results thus invite a comparison with the conditions under which Bugg and Smallwood (2016) obtained their pre-cueing effects. The most obvious difference between their and our experimental design may concern the moment of cue presentation (i.e., during the preceding trial versus during the interval between successive trials). Yet, at least three other design differences are also noticeable: (1) Bugg and Smallwood provided their participants with cues that conveyed explicit (and semantically transparent) information about their predictive value; (2) they used cues that predicted congruency levels with 100% validity; and (3) they compared the effect of these cues with performance on control blocks in which the cues were completely absent. In contrast, we were more interested in the question of whether participants could incidentally learn to get prepared for a predictable level of conflict, and so we adapted the conflict task to

include an implicit sequence learning paradigm, using the previous target as the informative cue, reducing the informative value of these cues to a validity of .80, and testing learning continuously over the same blocks, by comparing responses to regular vs. control trials.

Whereas these conditions produced clear effects of incidental learning when the probabilistic information concerned the identity of the following target (i.e., regular incidental sequence learning; Abrahamse et al., 2010), it turned out that participants were not equally able to exploit these cues when they informed them about the amount of conflict that they should face on the following trial. Future work may aim to tear apart the contributions of each of these differences in accounting for the contrasting patterns of results between the current study and the work by Bugg and Smallwood (2016).

The present results can also be considered surprising in comparison to previous CSPC and ISPC studies (Crump, Brosowsky, & Milliken, 2017; Crump & Milliken, 2009; Jacoby et al., 2003). Notice that the main effect of validity in our analyses corresponds to the two-way interaction between context/item (low versus high proportion congruency) and congruency, that is usually evaluated in studies focusing on the modulation of a congruency effect by cues (or contexts) that predict proportion congruency. Specifically, whereas in the present analysis cue conditions are categorized as a function of cue validity (standard practice in the sequence learning literature), CSPC and ISPC studies typically categorize cue conditions as a function of cue identity, and thus what it predicts (i.e., mostly congruent versus incongruent trials). As such, the here reported absent main effect of validity showed that participants in this task are not using that context to prepare for the congruency of the upcoming trial¹.

¹ Alternatively, concerns may be raised that our design lacks the necessary power to detect the size of the effect typically obtained in dedicated CSPC or ISPC experiments. CSPC designs are often found to produce absolute effects around 15-20 ms. In the present study, because the standard deviation of the differences between predicted and non-predicted trials in the color→congruency condition is 23 ms, this would amount to a normalized Cohen-d between .65 and .87. A design with 24 participants would be sufficiently high-powered

The main difference between studies showing item- or context-specific effects and the present study is probably that in the former studies the association occurs for control settings and stimulus features that are part of the same trial. Interestingly, together with the pre-cuing work discussed above, this suggests that the current null results for the color→congruency group could not be attributed to the cue-control set interval being either too short (as CSPC/ISPC effects use a zero interval; e.g., Crump & Milliken, 2009), or too long (as cueing studies used an even larger interval; e.g., 2000 ms in Bugg & Smallwood, 2016) for learning to develop. Instead, the main differences between the present procedure and previous studies could be best explained in terms of the structural differences provoked by presenting a prospective conflict-cue within the context of another conflict-related event, rather than in the context of the same event or as a separate cue (that may be encoded as part of the upcoming target event). Even though at this point it remains speculative, we believe the present results suggest that, for participants involved in a task that requires continuous shifts between conflict levels, it is especially difficult to use information from a previous event as a cue to prepare for the forthcoming conflict event. This type of event boundary condition is broadly consistent with other research on episodic memory suggesting that people show reduced memory for associations across versus within event boundaries (e.g., (Ezzyat & Davachi, 2011; Farrell, 2012; Kurby & Zacks, 2008). In that respect, cue-conflict associations could be easier to learn when part of the same episode because participants are more likely to cluster cue and target into a single memory trace. This type of reasoning also generally fits well with accounts that emphasized the role of episodic memories in explaining conflict adaptation (Egner, 2014; Schmidt, 2018; Schmidt, De Houwer, & Rothermund, 2016; Spapé & Hommel, 2008, 2014; Weissman, Hawks, & Egner, 2016)

to capture such effects ($1-\beta$ between .86 and .98, as computed by G*Power 3, Faul, Erdfelder, Lang, & Buchner, 2007), but it could be underpowered to detect effects of 10 ms ($1-\beta=.53$) or smaller.

(Egner, 2014; Schmidt, 2018; Schmidt, De Houwer, & Rothermund, 2016; Spapé & Hommel, 2008; 2014; Weissman, Hawks, & Egner, 2016).

Finally, one might argue that the absence of evidence for learning in the color→congruency group should not necessarily mean that learning was completely absent in this group, but rather that their effects were not strong enough to allow for their expression in speeded performance. In contrast to the color→color contingency, that involves a sequential relation between two relevant features and their corresponding responses, the color→congruency condition involves a more abstract relation between the color of each stimulus and the amount of conflict that will exist between that relevant feature and an irrelevant feature on the next stimulus. Even though we took care to make the information contents of each of these contingencies as comparable as possible, by allowing just two alternatives in each case (i.e., in the color→color group there was only a valid and an invalid successor for each predictor, just as in the color→congruency group there were only the two alternatives of congruent vs. incongruent successors), cross-dimensional forms of sequence learning have been typically harder to obtain, and have shown to give place to relatively smaller effects in performance (Schmidtke & Heuer, 1997; Shin, Aparicio, & Ivry, 2005). In this regard, however, it may be worth noting that Jiménez and Méndez (2013, Experiment 2a and 2b) also tested a condition that could be taken as an analogous, unidimensional version of this congruency sequence learning task, and they found no evidence of learning in their measures of speeded performance, even though their participants showed learning when they were asked about their explicit expectancies. In those experiments, the authors arranged the sequence of trials in either alternating or repeating series of congruency, so that the congruency level of each trial informed, with an average validity of .70, about the congruency level of its successor. Taking together these results by Jiménez and Méndez (2013) and the present results, it seems that using

information provided on a trial to prepare for the amount of conflict expected on the following trial is particularly difficult to achieve, at least under conditions in which the sequence information is conveyed by probabilistic cues.

In sum, the current findings show that sequential stimulus-conflict relations are not as easily formed as sequential stimulus-stimulus or response-response relations, which adds important nuance to recent learning-based theories of conflict adaptation that emphasize the shared underlying learning mechanisms between the two (Abrahamse et al., 2016; Egner, 2014). These findings are also particularly interesting in light of other studies showing stimulus-conflict relations within separate trial events (Bugg & Smallwood, 2016; Crump & Milliken, 2009), suggesting that the learning of stimulus-control relations is constrained by event boundaries. However, further research should determine whether providing more explicit or deterministic cues could produce any evidence of trial by trial, learning-based modulation of conflict control.

Compliance with Ethical Standards

The present research was funded by the Spanish Ministerio de Economía y Competitividad with a research grant to Luis Jiménez (PSI2015-70990-P). The authors declare that they have no conflict of interest. All procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

References

- Abrahamse, E., Braem, S., Notebaert, W., & Verguts, T. (2016). Grounding cognitive control in associative learning. *Psychological Bulletin*, *142*(7), 693–728. <https://doi.org/10.1037/bul0000047>
- Abrahamse, E. L., Jiménez, L., Verwey, W. B., & Clegg, B. A. (2010). Representing serial action and perception. *Psychonomic Bulletin and Review*, *17*(5), 603–623.

<https://doi.org/10.3758/PBR.17.5.603>

- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. <https://doi.org/10.1037/0033-295X.108.3.624>
- Bugg, J. M., & Smallwood, A. (2016). The next trial will be conflicting! Effects of explicit congruency pre-cues on cognitive control. *Psychological Research*, *80*(1), 16–33. <https://doi.org/10.1007/s00426-014-0638-5>
- Cañadas, E., Rodríguez-Bailón, R., Milliken, B., & Lupiáñez, J. (2013). Social categories as a context for the allocation of attentional control. *Journal of Experimental Psychology: General*, *142*(3), 934–943. <https://doi.org/10.1037/a0029794>
- Crump, M. J. C., Brosowsky, N. P., & Milliken, B. (2017). Reproducing the location-based context-specific proportion congruent effect for frequency unbiased items: A reply to Hutcheon and Spieler (2016). *The Quarterly Journal of Experimental Psychology*, *70*(9), 1792–1807. <https://doi.org/10.1080/17470218.2016.1206130>
- Crump, M. J. C., Gong, Z., & Milliken, B. (2006). The context-specific proportion congruent Stroop effect: Location as a contextual cue. *Psychonomic Bulletin & Review*, *13*(2), 316–321. <https://doi.org/10.3758/BF03193850>
- Crump, M. J. C., & Milliken, B. (2009). The flexibility of context-specific control: Evidence for context-driven generalization of item-specific control settings. *The Quarterly Journal of Experimental Psychology*, *62*(8), 1523–1532. <https://doi.org/10.1080/17470210902752096>
- D'Angelo, M. C., Jiménez, L., Milliken, B., & Lupiáñez, J. (2013). On the specificity of sequential congruency effects in implicit learning of motor and perceptual sequences. *Journal of Experimental Psychology: Learning Memory and Cognition*, *39*(1), 69–84. <https://doi.org/10.1037/a0028474>
- Deroost, N., & Soetens, E. (2006). Perceptual or motor learning in SRT tasks with complex sequence structures. *Psychological Research*, *70*((2)), 88–102. <https://doi.org/10.1007/s00426-004-0196-3>
- Deroost, N., Vandebossche, J., Zeischka, P., Coomans, D., & Soetens, E. (2012). Cognitive control: A role for implicit learning? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(5), 1243–1258. <https://doi.org/10.1037/a0027633>
- Egner, Tobias. (2014). Creatures of habit (and control): a multi-level learning perspective on the modulation of congruency effects. *Frontiers in Psychology*, *5*, 1247. <https://doi.org/10.3389/fpsyg.2014.01247>
- Egner, Tobias. (2017). Conflict adaptation: Past, present, and future of the congruency sequence effect as an index of cognitive control. In T. Egner (Ed.), *The Wiley Handbook of Cognitive Control* (pp. 64–78). Oxford: Wiley-Blackwell. <https://doi.org/doi:10.1002/9781118920497.ch4>
- Ezzyat, Y., & Davachi, L. (2011). What Constitutes an Episode in Episodic Memory? *Psychological Science*, *22*(2), 243–252. <https://doi.org/10.1177/0956797610393742>
- Farrell, S. (2012). Temporal clustering and sequencing in short-term memory and episodic

- memory. *Psychological Review*, *119*(2) 223-271), 223–271.
<https://doi.org/10.1037/a0027371>
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*.
- Frank, M. J., Loughry, B., & O'Reilly, R. C. (2001). Interactions between frontal cortex and basal ganglia in working memory: A computational model. *Cognitive, Affective and Behavioral Neuroscience*, *1*(2), 137–160. <https://doi.org/10.3758/CABN.1.2.137>
- Ghinescu, R., Schachtman, T. R., Stadler, M. A., Fabiani, M., & Gratton, G. (2010). Strategic behavior without awareness? Effects of implicit learning in the Eriksen flanker paradigm. *Memory & Cognition*, *38*(2), 197–205.
<https://doi.org/10.3758/MC.38.2.197>
- Gratton, G., Coles, M. G. H., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*, *121*(4), 480–506. <https://doi.org/10.1037/0096-3445.121.4.480>
- Howard, J. H., Mutter, S. A., & Howard, D. V. (1992). Serial Pattern Learning by Event Observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(5), 1029–1039. <https://doi.org/10.1037/0278-7393.18.5.1029>
- Inquisit 4 [Computer Software]. (2015). Retrieved from <https://www.millisecond.com>.
- Jacoby, L. L., Lindsay, D. S., & Hessels, S. (2003). Item-specific control of automatic processes: Stroop process dissociations. *Psychonomic Bulletin & Review*, *10*(3), 638–644. <https://doi.org/10.3758/BF03196526>
- JASP (Version 0.9)[Computer Software]. (2018). <https://doi.org/https://jasp-stats.org/>
- Jiménez, L., Lupiáñez, J., & Vaquero, J. M. M. (2009). Sequential congruency effects in implicit sequence learning. *Consciousness and Cognition*, *18*(3), 690–700.
<https://doi.org/10.1016/j.concog.2009.04.006>
- Jiménez, L., & Méndez, A. (2013). It is not what you expect: Dissociating conflict adaptation from expectancies in a stroop task. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 271–284.
<https://doi.org/10.1037/a0027734>
- Jiménez, L., & Méndez, A. (2014). Even with time, conflict adaptation is not made of expectancies. *Frontiers in Psychology*, *5*, 1042.
<https://doi.org/10.3389/fpsyg.2014.01042>
- Koch, I. (2001). Automatic and Intentional Activation of Task Sets. *Journal of Experimental Psychology: Learning Memory and Cognition*. <https://doi.org/10.1037/0278-7393.27.6.1474>
- Koch, I. (2005). Sequential task predictability in task switching. *Psychonomic Bulletin and Review*. <https://doi.org/10.3758/BF03196354>
- Koch, I. (2007). Anticipatory response control in motor sequence learning: Evidence from stimulus–response compatibility. *Human Movement Science*, *26*(2), 257–274.

<https://doi.org/https://doi.org/10.1016/j.humov.2007.01.004>

- Kurby, C. A., & Zacks, J. M. (2008). Segmentation in the perception and memory of events. *Trends in Cognitive Sciences*, *12*(2), 72–79. <https://doi.org/10.1002/cam4.334>
- Logan, G. D., & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*, *7*(3), 166–174. <https://doi.org/10.3758/BF03197535>
- MacLeod, C. M. (1992). The Stroop task: The “gold standard” of attentional measures. *Journal of Experimental Psychology: General*, *121*(1), 12–14. <https://doi.org/10.1037/0096-3445.121.1.12>
- Mayr, U. (1996). Spatial attention and implicit sequence learning: Evidence for independent learning of spatial and nonspatial sequences. *Journal of Experimental Psychology: Learning Memory and Cognition*, *22*(2), 350–364. <https://doi.org/10.1037/0278-7393.22.2.350>
- Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience*, *6*, 450–452. Retrieved from <http://dx.doi.org/10.1038/nn1051>
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, *19*(1), 1–32. [https://doi.org/10.1016/0010-0285\(87\)90002-8](https://doi.org/10.1016/0010-0285(87)90002-8)
- Norman, D. A., & Shallice, T. (1986). Attention to Action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and Self-Regulation: Advances in Research and Theory Volume 4* (pp. 1–18). New York: Plenum Press. https://doi.org/10.1007/978-1-4757-0629-1_1
- Notebaert, W., Gevers, W., Verbruggen, F., & Liefvoeghe, B. (2006). Top-down and bottom-up sequential modulations of congruency effects. *Psychonomic Bulletin & Review*, *13*(1), 112–117. <https://doi.org/10.3758/BF03193821>
- Remillard, G. (2003). Pure Perceptual-Based Sequence Learning. *Journal of Experimental Psychology: Learning Memory and Cognition*, *29*(4), 581–597. <https://doi.org/10.1037/0278-7393.29.4.581>
- Scherbaum, S., Fischer, R., Dshemuchadse, M., & Goschke, T. (2011). The dynamics of cognitive control: Evidence for within-trial conflict adaptation from frequency-tagged EEG. *Psychophysiology*, *48*(5), 591–600. <https://doi.org/10.1111/j.1469-8986.2010.01137.x>
- Schmidt, J. R. (2013). Questioning conflict adaptation: Proportion congruent and Gratton effects reconsidered. *Psychonomic Bulletin and Review*, *20*(4), 615–630. <https://doi.org/10.3758/s13423-012-0373-0>
- Schmidt, J. R. (2018). Evidence against conflict monitoring and adaptation: An updated review. *Psychonomic Bulletin & Review*. <https://doi.org/10.3758/s13423-018-1520-z>
- Schmidt, J. R., De Houwer, J., & Rothermund, K. (2016). The Parallel Episodic Processing (PEP) model 2.0: A single computational model of stimulus-response binding, contingency learning, power curves, and mixing costs. *Cognitive Psychology*, *91*, 82–

108. <https://doi.org/10.1016/j.cogpsych.2016.10.004>
- Schmidtke, V., & Heuer, H. (1997). Task integration as a factor in secondary-task effects on sequence learning. *Psychological Research, 60*(1–2), 53–71. <https://doi.org/10.1007/BF00419680>
- Shanks, D. R., Wilkinson, L., & Channon, S. (2003). Relationship Between Priming and Recognition in Deterministic and Probabilistic Sequence Learning. *Journal of Experimental Psychology: Learning Memory and Cognition, 29*(2), 248–261. <https://doi.org/10.1037/0278-7393.29.2.248>
- Shin, J. C., Aparicio, P., & Ivry, R. B. (2005). Multidimensional sequence learning in patients with focal basal ganglia lesions. *Brain and Cognition, 58*(1), 75–83. <https://doi.org/10.1016/j.bandc.2004.09.015>
- Song, S., Howard, J. H., & Howard, D. V. (2008). Perceptual sequence learning in a serial reaction time task. *Experimental Brain Research, 189*(2), 145–158. <https://doi.org/10.1007/s00221-008-1411-z>
- Spapé, M. M., & Hommel, B. (2008). He said, she said: Episodic retrieval induces conflict adaptation in an auditory Stroop task. *Psychonomic Bulletin and Review, 15*(6), 1117–1121. <https://doi.org/10.3758/PBR.15.6.1117>
- Spapé, M. M., & Hommel, B. (2014). Sequential modulations of the Simon effect depend on episodic retrieval. *Frontiers in Psychology, 5*. <https://doi.org/10.3389/fpsyg.2014.00855>
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662. <https://doi.org/10.1037/h0054651>
- Vaquero, J. M. M., Jiménez, L., & Lupiáñez, J. (2006). The problem of reversals in assessing implicit sequence learning with serial reaction time tasks. *Experimental Brain Research, 175*(1), 97–109. <https://doi.org/10.1007/s00221-006-0523-6>
- Verbruggen, F., McLaren, I. P. L., & Chambers, C. D. (2014). Banishing the Control Homunculi in Studies of Action Control and Behavior Change. *Perspectives on Psychological Science, 9*(5), 497–524. <https://doi.org/10.1177/1745691614526414>
- Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: dealing with specific and nonspecific adaptation. *Psychological Review, 115*(2), 518–525. <https://doi.org/10.1037/0033-295X.115.2.518>
- Verguts, T., & Notebaert, W. (2009). Adaptation by binding: a learning account of cognitive control. *Trends in Cognitive Sciences, 13*(6), 252–257. <https://doi.org/10.1016/j.tics.2009.02.007>
- Weissman, D. H., Hawks, Z. W., & Egner, T. (2016). Different levels of learning interact to shape the congruency sequence effect. *Journal of Experimental Psychology: Learning Memory and Cognition, 42*(4), 566–583. <https://doi.org/10.1037/xlm0000182>
- Wühr, P., & Kunde, W. (2008). Precueing spatial S-R correspondence: Is there regulation of expected response conflict? *Journal of Experimental Psychology: Human Perception and Performance, 34*(4), 872–883. <https://doi.org/10.1037/0096-1523.34.4.872>

