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Can't wait to relax: First-time evidence for a prospective relaxation of control as revealed by a future-based congruency sequence effect

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ABSTRACT

There is a growing interest in how cognitive control is regulated when explicit knowledge about upcoming conflict is available. In conflict tasks (e.g., Stroop), this regulation has been examined by cueing whether the distractor and the target in the upcoming trial will be congruent (e.g., the word RED in the color red) or incongruent (e.g., RED in blue). However, how this preparation impacts ongoing control recruitment has thus far been neglected. In the present study, we hypothesised that preparing a control state relevant for a future event (i. e., relaxed/tightened control for a future congruent/incongruent trial) would impact control recruitment in the present. We tested this idea by presenting trials of a conflict task in pairs. Before each pair, a cue either signalled Trial 2 congruency (with 100% validity) or provided no information. Even though the cue and Trial 2 were separated by an intervening trial, cueing benefits in Trial 2 suggested that cues were effectively used, expanding previous literature on congruency cues. More importantly, the congruency effect in Trial 1 was modulated by Trial 2 congruency when the latter was known. Specifically, the congruency effect was larger when Trial 2 was cued to be congruent vs. incongruent, a pattern similar to the congruency-sequence effect, but based on future, instructed (rather than past, experienced) congruency. These results suggest that preparing for a future event induces a prospective anticipation of the future-relevant control state. We discuss the roles of working memory and motivation in the emergence of such prospective control recruitment.

In daily life we often prepare for future events. We may make a grocery list before going to the supermarket or mentally rehearse a phone number before dialling it. As these examples illustrate, preparation implies carrying out some cognitive operations in the present to support future goals. Importantly however, preparing for the future often impacts ongoing cognitive operations. For example, we may shower more quickly if someone is waiting for us or check the clock more frequently before an important appointment. In other words, preparing a future event impacts our behaviour during intervening events prospectively.[1] Given that most cognitive paradigms are not designed to include such intervening events, we argue that the impact of preparation on ongoing behaviour has been underappreciated, particularly in the field of cognitive control.

Cognitive control is conceived as the set of processes allowing individuals to pursue goal-directed behaviour by directing attention toward task-relevant information (Norman & Shallice, 1986). In the lab, control processes are investigated using conflict paradigms such as the Stroop task, the flanker task, the Simon task, and the prime-probe task. Stimuli in these paradigms possess both a task-relevant feature, requiring a response, and a task-irrelevant feature, eliciting a prepotent but irrelevant response. When the two responses diverge (incongruent trials) performance costs arise compared to when they match (congruent trials). Such congruency effect is typically interpreted as a measure of the control mechanisms employed to suppress task-irrelevant information (MacLeod, 1991). Using conflict paradigms, much research has shown that *past* events impact control recruitment. An empirical example is the congruency sequence effect (CSE), namely the observation that the congruency effect is reduced following incongruent trials vs. congruent trials. The CSE is typically interpreted as evidence of control adaptation based on prior experience (Botvinick et al., 2001). Experiencing a congruent trial, where little control is needed, leads to control relaxation, and thus to a larger congruency effect in the

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[1] Here, we use the term “prospective” in a theoretically-neutral fashion. Although the term “proactive” is often used to describe a similar preparatory modulation of cognitive control (Braver, 2012), this term may not fully capture the effect under investigation here. We will return to this point in the Discussion.

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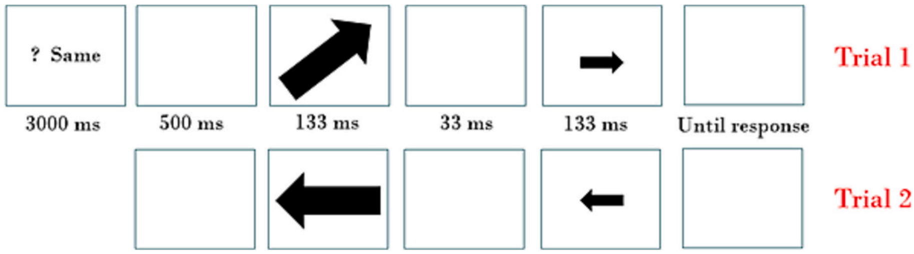

Fig. 1. Timing of events in a trial pair. *Note.* The figure shows a sample trial in informative-cue blocks, where Trial 2 congruency is cued at the beginning of the trial pair. The word "different" was used to indicate that Trial 2 would be incongruent. The word "same" was used to indicate that Trial 2 would be incongruent. Finally, the question mark was used to indicate that congruency of Trial 1 is unknown. In uninformative blocks, two question marks were used to indicate that congruency of both Trial 1 and Trial 2 was unknown.

subsequent trial. In contrast, experiencing conflict on incongruent trials prompts control tightening, thereby reducing the congruency effect in the subsequent trial. In brief, the CSE suggests that *past* experience impacts control recruitment in the present.

However, because control is also assumed to operate under novel circumstances (Norman & Shallice, 1986), it is reasonable to expect that information about upcoming events should likewise trigger control adaptation (Braem et al., 2024). Whether future-relevant information can be exploited to prepare a suitable control state (i.e., relaxed vs. tightened) has been examined using congruency cues. In these studies, explicit cues signal the upcoming stimulus' congruency. Compared to a condition where cues are uninformative, informative cues typically yield performance benefits in congruent trials (Bugg & Smallwood, 2016; Correa et al., 2009; Jiménez et al., 2021; Wühr & Kunde, 2008), suggesting that a relaxed control state can be prepared. For incongruent trials, the picture is more nuanced, as only a few studies reported cueing benefits when controlling for potential confounds (for a review: Bugg et al., 2026).

1.1. Extant evidence of prospective preparation

Although congruency cues are well-suited for investigating future-oriented control adaptation, their use has been limited to cueing congruency in the upcoming trial. This design does not enable to assess whether preparing a control state for a future event affects control recruitment during an intervening event, because no such event is included. However, it is plausible that maintaining a future-relevant control state in working memory induces a prospective form of control adaptation in the present, that an intervening event would be able to capture.

This idea is suggested by studies examining the role played by working memory in guiding future actions (Nobre & Stokes, 2019; Olivers & Roelfsema, 2020). In these studies, a stimulus requiring a delayed response is followed by another requiring an immediate response (Fournier et al., 2015; Mocke et al., 2024; Stoet & Hommel, 1999; Trentin et al., 2024). For example, participants may be presented with a first bar, and asked to report its orientation only after reporting the orientation of a second bar (Trentin et al., 2024). Typically responses to the first stimulus depends on the features of the second, such as whether the second stimulus requires the same type of action (e.g., gripping vs. sliding), suggesting an interaction between working-memory representations and action control. Similarly, in dual-tasking paradigms two stimuli are presented sequentially, each requiring to perform a different task (Koch et al., 2018). Performance in the first task declines if the second task requires a different response (the backward-crosstalk effect: Hommel, 1998). Finally, a related strand of research has investigated the influence of future-relevant S-R mappings on current task execution. In these studies, before each mini-block, participants are instructed about two new tasks. In the first portion of each mini-block only one task is required (diagnostic task), while the other task becomes relevant in the second portion (inducer task). Because both tasks typically employ the same stimuli and response-sets, it is possible to test whether the future-relevant inducer task interferes with the diagnostic task. Consistent with this prediction, performance in the diagnostic task declines when the stimulus primes a different response in the inducer task (Liefooghe et al., 2012; Meiran et al., 2015). Overall, these findings suggest that *what* we plan to do next affects performance in the present. However, they offer little insight into whether preparing a control state (i.e., *how* to do something) influences ongoing cognitive processes.

1.2. The present study

To summarise, previous literature suggests that control recruitment is affected by past experience (as indexed by the CSE) and information about upcoming events (as reflected by cueing benefits). Furthermore, evidence has accumulated that future action plans (i.e., *what* to do) influence current actions. However, no study has yet investigated how information about future events affects control recruitment (i.e., *how* to do something) in the present.

To address this gap, we modified a prime-probe task by chunking the trial list into trial pairs. Before each trial pair, a cue indicated either the congruency of Trial 2 or provided no information. This paradigm can reveal 1) whether participants prepare for a trial that is not imminent (i.e., Trial 2) and 2) whether such preparation impacts control recruitment in Trial 1. If both predictions hold, we should observe 1) Cueing benefits in Trial 2, suggesting that cues were effectively used and 2) A larger congruency effect in Trial 1 when Trial 2 is cued to be congruent vs. incongruent. The latter prediction stems from the idea that maintaining future congruency in working memory may influence control recruitment in the present. Specifically, when Trial 2 is cued to be congruent, participants may relax control already in Trial 1. Complementarily, an incongruent cue may induce a prospective tightening of cognitive control. In other words, we expect a pattern analogous to the CSE, but driven by future rather than past congruency. We thus label this effect *future-based CSE.*[2]

2. Methods

Three experiments were conducted using a highly similar design. Experiment 2 was a pre-registered (https://aspredicted.org/rgj3-fh73.pdf) direct replication of Experiment 1. Experiment 3 (https://aspredicted.org/8fyy-9v9x.pdf) was identical to Experiments 1–2, except that each participant received a unique sequence of trials rather than

[2] Notice that the term future-based CSE is used descriptively, to indicate a pattern of results that is similar to the (past-based) CSE. Both effects are driven by control adjustments, and thus are likely to stem from the same mechanisms (i.e., an adjustment in attentional weighting depending on past or future congruency). However, they fundamentally differ in the trigger of control adjustments, being either instructed, future conflict (future-based CSE), or experienced, past conflict (CSE).

using the same sequence to all participants within a counterbalancement condition (see below).

2.1. Participants

Given the novelty of the effect under investigation, we assumed the future-based CSE to have an effect size of $d_z = 0.4$, as this was suggested to be the average effect size in psychology (Brysbaert, 2019). To reach 80% power, we kept collecting data until we reached 52 analyzable datasets according to our data-trimming criteria (see below) in each experiment.[3] In total, 180 participants were recruited on Prolific (Mean age 27.2 $\pm$ 4.87, 57% females) in exchange for monetary compensation (10€).

2.2. Task and stimuli

Participants completed a prime-probe paradigm similar to that used in Weissman et al.'s (2015) Experiment 1, which produced a large (past-based) CSE. As for the cueing manipulation, we used a similar procedure to Bugg and Smallwood (2016), with some modifications dictated by the present design. The procedure is depicted in Fig. 1. Before each trial pair, a cue appeared for 3000 ms, indicating either the congruency of Trial 2 (informative-cue condition) or that the congruency of both trials was unknown (uninformative-cue condition). To this end, congruency cues were composed of two elements. A question mark on the left indicated that Trial 1 congruency was unknown (which was always the case). On the right, the words "same" or "different", indicated that Trial 2 would be congruent or incongruent in the informative-cue condition, whereas a question mark indicated that Trial 2 congruency was unknown in the uninformative condition. Participants were informed that, unless specified otherwise by the cue, any trial was equally likely to be congruent or incongruent. Informative cues were 100% valid. After cue presentation, Trial 1 started with a 500-ms blank screen. Next, a large prime arrow appeared for 133 ms, followed by a blank screen for 33 ms, and a smaller probe arrow for another 133 ms. Participants had to indicate the direction of the probe arrow within 1500 ms. When a response was produced, or after this time had elapsed, Trial 2 began with the same event timing.

In order to avoid repetition-priming confounds when analysing Trial 2 performance, different stimulus (and response) sets were used in Trial 1 and Trial 2 (Braem et al., 2019). In one of the two trials the prime and probe arrows always pointed left (either up-left, center-left, or down-left), whereas in the other trial the arrows always pointed right (either up-right, center-right, or down-right). The trial-stimulus set relationship was counterbalanced across participants. Responses were spatially compatible with the arrow directions. Specifically, left-pointing arrows were responded with the left hand using the R, F and V keys, whereas right-pointing arrows were responded with the right hand using the I, J and N keys (cf. Spinelli et al., 2022; Spinelli & Lupker, 2024). Using three response alternatives for each trial was needed to exclude the possibility for participants to use incongruent cues to prepare a response opposite to the task-irrelevant feature, which is possible with two response options (Wühr & Kunde, 2008).

2.3. Experimental procedure

After receiving instructions, participants performed a first practice block consisting of 12 trial-pairs, without congruency cues (a 3000 ms blank screen was presented instead). After this phase, participants were told that in the task there were two types of trials: In "same" (i.e., congruent) trials the two arrows would point in the same direction, whereas in "different" (i.e., incongruent) trials they would not. Following this explanation, 10 trials were presented in which participants only had to indicate the stimulus congruency, without performing the prime-probe task. To advance to the next phase, at least 8 correct responses had to be provided (all participants met this criterion). Lastly, a final practice phase introduced congruency cues. Participants were told that from that point on, before each trial pair, a cue would either inform them about Trial 2 congruency, or of neither trials. We explicitly encouraged participants to use the informative-cue information to best perform Trial 2. In the test phase, 4 informative and 4 uninformative blocks were presented consecutively, each consisting of 48 trial-pairs (768 trials in total). The block order was counterbalanced across participants. Both the informative-cue and uninformative-cue halves were preceded by a practice session of 12 trial-pairs with the corresponding cue type. Trial sequences were built pseudo-randomly equating the number of congruent and incongruent trials in both Trial 1 and Trial 2, and ensuring that each stimulus (i.e., each individual prime-probe combination) was presented equally often. Additionally, in Trial 2 each stimulus was presented equally often after a congruent or an incongruent stimulus. In Experiment 1 and 2, the same trial sequence was used for all participants within a counterbalancement (i.e., 4 unique sequences were built). In Experiment 3, a different sequence was assigned to each participant (i.e., 56 sequences, 14 for each counterbalancement). Experiment 3 was run to rule out that the observed effects were due to the specific sequences used.

2.4. Statistical design

We ran two sets of analyses. The first set served as a manipulation check aimed at verifying that congruency cues were effectively used when performing Trial 2. If they were, performance should improve in informative-cue blocks compared to uninformative-cue blocks. In line with much previous literature, however, cueing benefits might be found exclusively for congruent cues. To assess these possibilities we ran separate 2 $\times$ 2 within-subjects ANOVAs with RTs and arcsine-squared root error rates (Laurencelle & Cousineau, 2023) in Trial 2 as dependent variables, and with Trial 2 Congruency (congruent, incongruent), and Block Type (informative cues, uninformative cues) as factors.[4]

The second set of analyses was conducted to test our core prediction, namely that preparing a future-relevant control state affects ongoing control recruitment. If this is true, we should observe that control recruitment in Trial 1 is modulated by Trial 2 congruency when the latter is known in advance. Specifically, in informative-cue blocks, the congruency effect should be larger when Trial 2 is cued to be congruent (and/or reduced when Trial 2 is cued to be incongruent). To test this prediction, we ran separate 2 $\times$ 2 $\times$ 2 within-subjects ANOVAs with RTs

[3] We originally pre-registered that, in order to reach a sample size of 52 analyzable participants, we would recruit 56 participants in each experiment. However, because the final sample size after data trimming was slightly smaller than 52 (i.e., 51 in Experiment 1, 50 in Experiment 2 and 45 in Experiment 3), an anonymous reviewer recommended collecting additional data until the target sample size was reached. Compared to the pre-registered data collection plan, the results did not change in any meaningful way.

[4] Notice that in our pre-registration protocols we also planned to include Trial 1 congruency as an independent variable when analysing Trial 2 performance. This was because, as a secondary aim of our study, we also intended to verify whether the classic CSE would be modulated by cue informativeness. In fact, some accounts of the CSE posit that this effect emerges from the fact that participants expect congruency to repeat across two consecutive trials (Gratton et al., 1992). These expectations would be advantageous when congruency actually repeats, but they would lead to costs when congruency switches, thus generating the CSE. This account would therefore predict the CSE to be abolished in Trial 2 when congruency cues were provided, as the explicit expectations of the participants about upcoming congruency would never be violated (because the cues were 100% valid in our experiment). We report the pre-registered analyses including Trial 1 congruency in the Appendix. As can be seen, contrary to the expectation-based account of the CSE, the CSE emerged in informative-cue blocks as strongly as it did in uninformative-cue blocks.

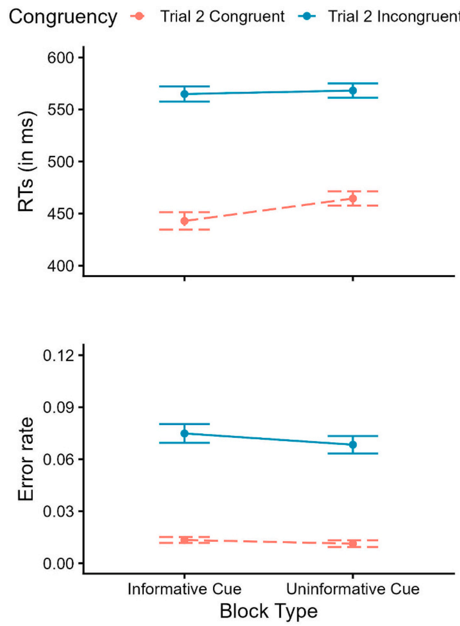

Fig. 2. Descriptive statistics for Trial 2 performance. Error bars represent the standard error of the mean.

Table 1
ANOVA effects for Trial 2 analysis.

	RTs	*Error rates*
Trial 2 Congruency	$F(1, 155) = 1709.17, p < .001, \eta_p^2 = 0.92$	$F(1, 155) = 374.30, p < .001, \eta_p^2 = 0.71$
Block Type	$F(1, 155) = 11.58, p < .001, \eta_p^2 = 0.07$	$F(1, 155) = 2.59, p = .110, \eta_p^2 = 0.02$
Trial 2 Congruency x Block Type	$F(1, 155) = 35.37, p < .001, \eta_p^2 = 0.19$	$F(1, 155) < 1$

and arcsine-squared root error rates in Trial 1 as dependent variables, and with Trial 1 Congruency (congruent, incongruent), Trial 2 Congruency (congruent, incongruent) and Block Type (informative cues, uninformative cues) as factors.

Given the high similarity between experiments and the consistency of their results, here we present an aggregated-data analysis.[5] Results of individual experiments are available in the Appendix.

3. Results

3.1. Data trimming

During data trimming, we excluded all trials in which no response was provided within the response deadline (2.5%), responses below 150 ms (1.0%), and incorrect responses from the RT analyses. We additionally removed post-error trials from Trial 2 analyses (12.4%). Finally, we excluded all data from participants with less than 75% correct responses (five participants in Experiment 1, five in Experiment 2, and twelve in Experiment 3), and from participants with less than 20 remaining trials in any cell of the design (one participant in Experiment 2 and one in Experiment 3).

3.2. Trial-2 analyses

Descriptive statistics are depicted in Fig. 2. ANOVA results are summarised in Table 1.

In the RTs we observed a main effect of Trial 2 Congruency, confirming the occurrence of a congruency effect (567 ms in incongruent trials vs. 454 ms in congruent trials), and a main effect of Block Type, indicating overall cueing benefits (504 ms in informative-cue blocks vs. 516 ms in uninformative-cue blocks). This effect interacted with Trial 2 Congruency, indicating that such benefits were observed in congruent trials (22 ms), $t(155) = 4.52$, $p < .001$, $d_z = 0.36$, but not in incongruent trials (3 ms), $t(155) = 1.12$, $p = .265$, $d_z = 0.09$.

In the error rates, only the main effect of Trial 2 Congruency reached significance, indicating the classic congruency effect (7.1% in incongruent trials and vs. 1.2% in congruent trials).

3.3. Trial-1 analyses

Descriptive statistics of Trial 1 performance are depicted in Fig. 3. ANOVA results are summarised in Table 2. Here we only focus on RTs analyses, as the error data closely mimic the most relevant results.

In the RTs, the main effect of Trial 1 Congruency was significantly modulated by an interaction with Trial 2 Congruency, revealing a CSE-like pattern with a larger congruency effect *before* a congruent trial (111 ms) than *before* an incongruent one (107 ms) (i.e., a future-based CSE). Importantly, this interaction was further modulated by Block Type. We

[5] To ensure that no significant differences emerged between experiments, we ran the same analyses reported in the manuscript including Experiment as a between-subjects factor. Experiment did not interact with any of the theoretically-relevant effects. In Trial-2 analyses, Experiment did not modulate the effect of Block Type, nor the interaction between Block Type and Trial 2 Congruency. In Trial-1 analyses, Experiment did not modulate the Trial 1 Congruency x Trial 2 Congruency interaction, nor the 3-way interaction between Trial 1 Congruency, Trial 2 Congruency and Blok Type.

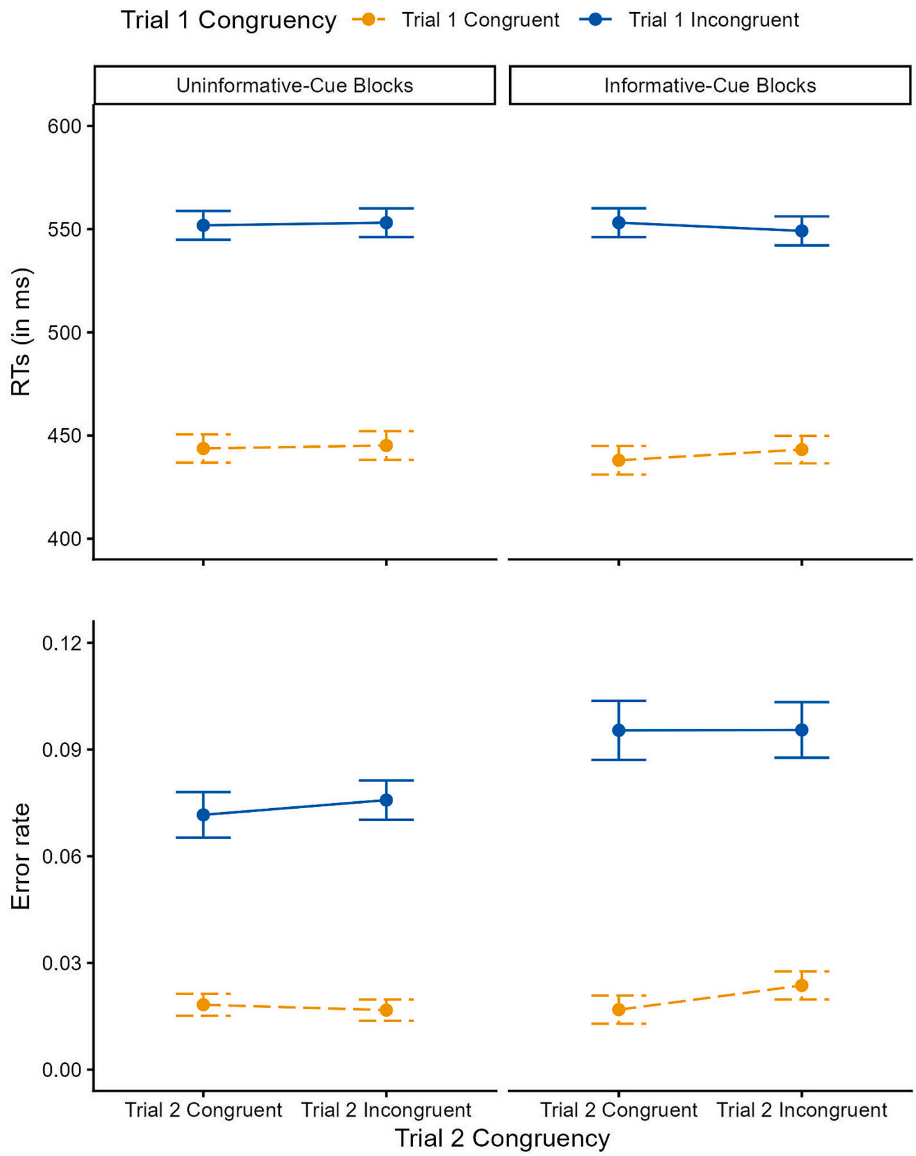

Fig. 3. Descriptive statistics for Trial 1 performance. Error bars represent the standard error of the mean.

Table 2
ANOVA effects for Trial 1 analysis.

	RTs	*Error rates*
Trial 1 Congruency	$F(1, 155) = 1815.65$, $p <$ .001, $\eta_p^2 = 0.92$	$F(1, 155) = 322.09$, $p <$ .001, $\eta_p^2 = 0.68$
Trial 2 Congruency	$F(1, 155) = 1.70$, $p =$ .194, $\eta_p^2 = 0.01$	$F(1, 155) = 5.08$, $p =$ .026, $\eta_p^2 = 0.03$
Block Type	$F(1, 155) < 1$	$F(1, 155) = 6.98$, $p =$ .009, $\eta_p^2 = 0.04$
Trial 1 Congruency x Trial 2 Congruency	$F(1, 155) = 12.30$, $p <$ .001, $\eta_p^2 = 0.07$	$F(1, 155) < 1$
Trial 1 Congruency x Block Type	$F(1, 155) = 1.48$, $p =$ .226, $\eta_p^2 < 0.01$	$F(1, 155) = 7.86$, $p =$ .006, $\eta_p^2 = 0.05$
Trial 2 Congruency x Block Type	$F(1, 155) < 1$	$F(1, 155) = 3.45$, $p =$ .065, $\eta_p^2 = 0.02$
3-way interaction	$F(1, 155) = 8.43$, $p =$ .004, $\eta_p^2 = 0.05$	$F(1, 155) = 9.86$, $p =$ .002, $\eta_p^2 = 0.06$

explored this three-way interaction in two ways. First, we split the data by Block Type and ran separate 2 × 2 ANOVAs with Trial 1 Congruency and Trial 2 Congruency as factors. This analysis allowed us to confirm that the future-based CSE was only observed in informative-cue blocks (the congruency effect was 115 ms before a congruent trial vs. 106 ms before an incongruent trial), $F(1, 155) = 19.19$, $p < .001$, $\eta_p^2 = 0.11$, but not in uninformative-cue blocks, in which Trial 2 congruency impacted neither the congruency effect, $F(1, 155) < 1$, nor performance in general, $F(1, 155) = 1.69$, $p = .195$, $\eta_p^2 = 0.01$.

Second, we split the data by each level of Trial 2 Congruency and ran separate ANOVAs with Trial 1 Congruency and Block Type as factors. This analysis allowed us to determine whether the observed future-based CSE in informative-cue blocks was driven by congruent cues, incongruent cues, or both. The results suggested a role for congruent cues only: When Trial 2 was congruent, the interaction between Trial 1 Congruency and Block Type was significant, $F(1, 155) = 6.34$, $p = .013$, $\eta_p^2 = 0.04$, indicating that the congruency effect in Trial 1 was larger in informative-cue blocks (115 ms) compared to uninformative-cue blocks (108 ms). The parallel interaction effect was absent when Trial 2 was incongruent, $F(1, 155) < 1$.

4. Discussion

The present study had two aims. First, we intended to establish whether congruency cues are still exploited when preparing for a trial that is not imminent. Second, and most importantly, we hypothesised that the control processes elicited by the cue would interact with ongoing control processes in a prospective manner. In particular, we predicted that the need to prepare a control state (relaxed or tightened) for Trial 2 would lead individuals to anticipate that control state to Trial 1, thus generating an effect akin to the CSE, but based on future congruency.

Our results support both predictions. Performance in Trial 2 improved in informative-cue blocks, providing evidence that congruency cues were effectively exploited even if they did not refer to an imminent trial. Consistent with much previous literature, however, cueing benefits were limited to congruent trials (Correa et al., 2009; Gratton et al., 1992; Wühr & Kunde, 2008), suggesting that participants were able to relax, but not tighten, cognitive control. The differential efficacy of congruent vs. incongruent cues likely stems from the fact that in congruent trials, but not in incongruent trials, the task-irrelevant feature provides the correct response. In line with this idea, cueing benefits for incongruent trials are often observed in two-choice paradigms (Aarts et al., 2008; Ghinescu et al., 2010; Wühr & Kunde, 2008), where participants can use incongruent cues to prepare a response opposite to the task-irrelevant feature, but are harder to observe with paradigms using at least three response options such as ours. Therefore, our results align with studies cueing congruency in the upcoming trial.

The most novel finding of our study, however, is the observation of a future-based CSE in informative-cue blocks. As predicted, the congruency effect in Trial 1 was larger with Trial 2 congruent vs. incongruent cues. This finding suggests that receiving information about which control state will be most appropriate in the future impacts control recruitment in the present. Moreover, we found that the future-based CSE was exclusively driven by Trial 2 congruent cues, with Trial 2 incongruent cues having no impact. This fits nicely with the finding, noted above, that only Trial 2 congruent cues were effectively used. Therefore, preparing a future-relevant control state seems to impact an intervening event only when preparation does take place.

The question these results raise is how such form of preparation can impact an intervening event. One possibility is that the future-based CSE stems from active maintenance of the cue information in working memory. As discussed, previous research suggests that holding information about future actions interacts with current performance, so that congruent actions are performed faster and more accurately (Hommel, 1998; Trentin et al., 2024). In our experiments, holding the relevant control parameters for Trial 2 in working memory may have caused benefits in Trial 1 when the cue information matched the control state relevant in this trial, and costs when it mismatched. An alternative but related possibility is that the cue information presented before Trial 1 impacted Trial 1 processing without the need of active working-memory maintenance. Indeed, cue presentation may have triggered the corresponding control state in a bottom-up fashion (e.g., seeing "similar" may automatically trigger control relaxation). This account slightly differs from the active-maintenance account presented above, as it implies that the future-relevant control state passively carries over to Trial 1. However, because passive carryover may be subject to decay, the fact that cueing benefits emerged in Trial 2 seems to be more consistent with an active preparation process.

Finally, the future-based CSE might have emerged from a strategic anticipation of the control state relevant in Trial 2 to Trial 1. Ideally, in our paradigm participants should disregard the cue when executing Trial 1, and retrieve it during the interval between Trial 1 and Trial 2. When congruency switches from Trial 1 to Trial 2, however, the control settings implemented in Trial 1 would need to be updated for efficient performance of Trial 2. As the existence of the CSE suggests, such control updating is a potentially resource-demanding operation (Ileri-Tayar et al., 2025), which may be difficult to implement in the short interval between trials (500 ms). Therefore, participants are faced with a prioritization dilemma: Either disregard the cue to optimize performance in Trial 1, or anticipate the control state relevant to Trial 2 to Trial 1 so to optimize performance in Trial 2. Since we provided congruency cues for Trial 2, and encouraged participants to use them, performance in that trial was arguably more salient. Therefore, participants may solve the prioritization dilemma by opting for anticipating the control settings relevant in Trial 2 to Trial 1. This strategic account aligns well with the expected-value of control theory (Shenhav et al., 2013), which stresses the role of motivation for the recruitment of cognitive control. Specifically, the theory posits that the costs of control recruitment are traded-off against a perceived gain. Accordingly, in order to avoid the costs of switching control state, participants may decide to simply perform both trials with the same control state, guided by a higher motivation for performing Trial 2 accurately. Moreover, this strategy may not be adopted when Trial 2 is cued to be incongruent, as such a sustained control tightening is known to be costly.

4.1. Future directions and relation to existing theories

While the present experiments do not allow us to distinguish between the different accounts presented above, our paradigm can be modified to this aim. On the one hand, the role of strategic adaptation can be elucidated by manipulating experimental factors that may impact the need for anticipating the future-relevant control state to Trial 1, such as the time interval between trials, or the motivational saliency of Trial 2. On the other hand, the role of working-memory maintenance could be investigated by manipulating working-memory load, or by presenting longer sequences of trials in which only the last one is cued (i.e., by prolonging the time scale over which the cue information needs to be maintained).

Distinguishing between these accounts would not only help elucidating the mechanisms behind the future-based CSE, rather it would also clarify the relation between the present findings and existing cognitive-control theories. As mentioned in the introduction, previous research has neglected the impact of future information on ongoing control operations. This is reflected in mechanistic models of control adaptation that have exclusively focused on the role of past experience in triggering control recruitment (e.g., Botvinick et al., 2001; Kalanthroff et al., 2018; Verguts & Notebaert, 2009). Clarifying the role of working memory and strategic factors in eliciting the future-based CSE would be crucial for extending these models to include control modulations elicited by future-relevant information. Furthermore, future research should clarify how the present findings relate to control theories emphasizing the role of preparation. For example, the popular dual-model of control framework (Braver, 2012) postulates that control can be engaged proactively by keeping task-relevant information in working memory when this is (likely) relevant for an upcoming event (i.e., the very next trial). The present findings may be interpreted as a further characterization of this theory, showing for the first time that proactive control can be engaged even if the information being proactively maintained is not relevant for the upcoming event, but for a later event.[6] Note, however, that at present it is unclear whether the future-based CSE stems from proactive control mechanisms. In fact, not all the mechanistic accounts outlined in the previous section invoke proactive-control mechanisms. For example, the idea that the future-based CSE may emerge from a strategic anticipation of control settings is not related to the proactive-reactive distinction, but is rather rooted in control theories emphasizing the role of motivation and effort in control adaptation (Ileri-Tayar et al., 2025; Shenhav et al., 2013). Unveiling the specific mechanisms behind the future-based CSE would therefore enable to clarify the relationship between the present findings and existing control theories.

5. Conclusions

To conclude, the present study shows for the first time that preparing future-relevant control states has an impact on control recruitment in the present. Our results significantly expand the rich landscape of control adaptation beyond the known role of past experience. Further research should aim at elucidating the mechanisms behind the future-based CSE, as well as clarifying the link between the present findings and existing control theories.

CRediT authorship contribution statement

Luca Moretti: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Giacomo Spinelli:** Writing – review & editing, Methodology, Conceptualization.

Consent to participate

All participants gave written informed consent before participating.

Consent for publication

All participants gave written consent to the publication of their data in an anonymized form.

Ethics approval

The procedure of all experiments received the approval of the ethics committee of the Faculty of Arts and Humanities at RWTH Aachen University (approval number 2024_06_FB7_RWTH AACHEN).

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Declaration of competing interest

The authors have no competing interests to declare.

Appendix A. Results of individual experiemnts

In the appendix we report the results of each experiment separately. Note that, following the pre-registration protocols, the analyses of Trial 1 are conducted only on the informative-cue blocks, including Trial 1 congruency (congruent, incongruent) and Trial 2 congruency (congruent, incongruent) as within-subjects independent variables. Therefore, compared to the analyses on aggregated data reported in the main text, we do not include Block Type as an independent variable, but rather we aim to simply assess whether the future-based CSE emerged in the informative-cue blocks.

Also note that, as explained in footnote 5, and in line with our pre-registration protocols, the analyses of Trial 2 performance also include Trial 1 congruency. The reason is that, albeit secondary, one aim of the present experiments was to assess the possible impact of congruency cues on the classic CSE. Note that, when including this additional factor in the aggregated-data analysis reported in the main text, our results do not change substantially.

A.1. Experiment 1

A.1.1. Trial 1 analyses

Descriptive statistics of Trial 1 performance are presented in Table A1 for all experiments. In the RT analysis we found a main effect of Trial 1 Congruency, $F(1, 51) = 567.33$, $p < .001$, $\eta_p^2 = 0.92$, indicating the expected congruency effect. Importantly, Trial 1 Congruency and Trial 2 Congruency interacted, $F(1, 51) = 8.69$, $p = .005$, $\eta_p^2 = 0.15$, indicating the emergence of a future-based CSE overall. Follow-up comparisons revealed that this pattern was due to both congruent trials being significantly slower when Trial 2 was incongruent vs. congruent (−4 ms), $t(51) = 2.03$, $p = .048$, $d_z = 0.28$, and incongruent trials being significantly *faster* when Trial 2 was incongruent vs. congruent (4 ms), $t(51) = 2.15$, $p = .036$, $d_z = 0.30$.

In the error rates analyses, the main effect of congruency was again significant, $F(1, 51) = 172.60$, $p < .001$, $\eta_p^2 = 0.77$. The main effect of Trial 2 congruency also reached significance, $F(1, 51) = 5.88$, $p = .019$, $\eta_p^2 = 0.10$, with overall more errors before an incongruent trial. The 2-way interaction between these factors was not significant $F(1, 51) < 1$.

[6] Notice that this is a meaningful expansion of the vast literature on proactive control adaptation. Although proactive control is known to operate on time-scales longer than a single trial, the existent literature has never investigated the target of such proactive preparation. For example, the finding that the congruency effect is reduced in blocks where incongruent trials are the majority has been taken to suggest that participants prepare for conflict in a sustained fashion over multiple trials. However, it is currently impossible to determine whether such preparation is targeted to all future events (i.e., because most trials are incongruent, participants tighten control to best perform in the whole list), or rather to the upcoming trial (i.e., because most trials are incongruent, participants tighten control to best perform the upcoming trial). If interpreted within the DMC framework, the present findings are the first to demonstrate that proactive control can not only be devoted to preparing the upcoming trial, but to future events more generally.

Table A1
Descriptive statistics for Trial 1 performance in all experiments. Number reported in parenthesis represent the standard deviation.

		Trial 2 congruent		*Trial 2 incongruent*	
		Trial 1 Congruent	*Trial 1 Incongruent*	*Trial 1 Congruent*	*Trial 1 Incongruent*
Experiment 1	RTs	411 (46)	530 (55)	415 (44)	526 (54)
	Errors	1.1 (1.8)	9.8 (8.4)	1.8 (2.2)	10.3 (7.1)
Experiment 2	RTs	449 (100)	565 (98)	455 (97)	562 (102)
	Errors	2.3 (7.1)	10.3 (12.8)	2.9 (7.2)	9.9 (11.1)
Experiment 3	RTs	454 (98)	564 (99)	458 (93)	558 (95)
	Errors	1.8 (4.6)	8.6 (9.8)	2.5 (4.3)	8.4 (10.7)

A.1.2. Trial 2 analyses

Descriptive statistics for Trial 2 performance are represented in Fig. A1. All main effects reached significance. In particular, the main effect of Trial 2 Congruency indicated the expected congruency effect, $F(1, 51) = 627.64$, $p < .001$, $\eta_p^2 = 0.92$. The main effect of Trial 1 Congruency indicated that performance was faster when the previous trial was congruent, $F(1, 51) = 80.65$, $p < .001$, $\eta_p^2 = 0.61$. Finally, the main effect of Block Type indicated that performance was overall faster in blocks where informative cues were provided, $F(1, 51) = 8.52$, $p = .005$, $\eta_p^2 = 0.14$, an overall cueing effect. Importantly however, Block Type and Trial 2 Congruency interacted, $F(1, 51) = 12.13$, $p = .001$, $\eta_p^2 = 0.19$, indicating that the cueing effect was only observed for congruent trials (28 ms), $t(51) = 3.34$, $p = .001$, $d_z = 0.46$, but not for incongruent trials (7 ms), $t(51) = 1.62$, $p = .111$, $d_z = 0.23$. Finally, we observed a regular CSE as indicated by the interaction between Trial 1 Congruency and Trial 2 Congruency, $F(1, 51) = 198.21$, $p < .001$, $\eta_p^2 = 0.80$.

In the error rates we again observed the main effects of Trial 2 Congruency, $F(1, 51) = 169.14$, $p < .001$, $\eta_p^2 = 0.77$, and Trial 1 Congruency, $F(1, 51) = 38.95$, $p < .001$, $\eta_p^2 = 0.43$. These effects interacted significantly indicating the occurrence of the CSE, $F(1, 51) = 42.59$, $p < .001$, $\eta_p^2 = 0.46$. No other effect reached significance, $Fs < 1$.

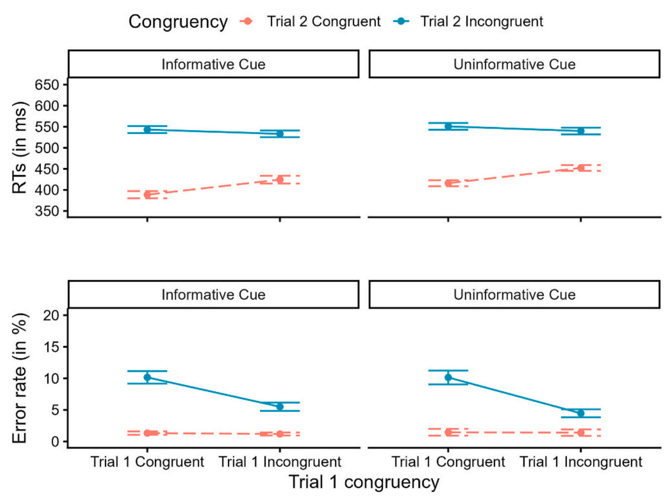

Fig. A1. Experiment 1: Descriptive statistics for Trial 2 performance. Error bars represent the standard error of the mean.

A.2. Experiment 2

A.2.1. Trial 1 analyses

Descriptive statistics for Trial 1 performance are reported in Table A1. The pattern of results largely replicated Experiment 1. We found a main effect of Trial 1 Congruency, $F(1, 51) = 489.16$, $p < .001$, $\eta_p^2 = 0.91$, revealing a robust congruency effect. Trial 2 Congruency had no impact on performance overall, $F(1, 51) < 1$. Crucially however, we replicated the interaction between Trial 1 Congruency and Trial 2 Congruency, $F(1, 51) = 5.60$, $p = .022$, $\eta_p^2 = 0.10$, reflecting a larger congruency effect in Trial 1 before a congruent vs. incongruent trial. Follow-up comparisons revealed that, in this case, the effect was mainly driven by slower performance in congruent trials when Trial 2 was incongruent vs. congruent (−6 ms), $t(51) = 2.52$, $p = .029$, $d_z = 0.31$. Performance in incongruent trials was again numerically faster when Trial 2 was incongruent vs. congruent (3 ms), but not significantly so, $t(51) = 1.34$, $p = .184$, $d_z = 0.19$.

In the error rates analyses, the main effect of Trial 1 Congruency was the only one to reach significance, $F(1, 51) = 57.35$, $p < .001$, $\eta_p^2 = 0.53$. Neither the main effect of Trial 2 Congruency, $F(1, 51) = 1.91$, $p = .173$, $\eta_p^2 = 0.04$, nor the interaction between Trial 1 Congruency and Trial 2 Congruency, $F(1, 51) = 2.44$, $p = .124$, $\eta_p^2 = 0.05$, were significant.

A.2.2. Trial 2 analyses

Descriptive statistics for Trial 2 performance are represented in Fig. A2. The main effects of Trial 2 Congruency, $F(1, 51) = 572.68$, $p < .001$, $\eta_p^2 = 0.92$, and Trial 1 Congruency, $F(1, 51) = 67.13$, $p < .001$, $\eta_p^2 = 0.57$, indicated that performance was overall faster when a congruent stimulus was present in either trial. These effects interacted showing the classic CSE pattern as in Experiment 1, $F(1, 51) = 142.04$, $p < .001$, $\eta_p^2 = 0.74$. The main effect of Block Type was not significant, $F(1, 51) = 1.72$, $p = .195$, $\eta_p^2 = 0.04$, indicating that no cueing benefits were present overall. However, we replicated the 2-way interaction between Trial 2 Congruency and Block Type, $F(1, 51) = 14.52$, $p < .001$, $\eta_p^2 = 0.22$. While performance improved in congruent trials when cued (19 ms), $t(51) = 2.15$, $p = .036$, $d_z = 0.30$, no such improvement was observed in incongruent trials (0 ms), $t(51) < 1$.

In the error rates we again observed the main effects of Trial 2 Congruency, $F(1, 51) = 78.87$, $p < .001$, $\eta_p^2 = 0.61$, and Trial 1 Congruency, $F(1, 51) = 10.80$, $p = .002$, $\eta_p^2 = 0.17$. These effects interacted significantly indicating the occurrence of the CSE, $F(1, 51) = 35.58$, $p < .001$, $\eta_p^2 = 0.41$. No other effect reached significance, $Fs < 1$.

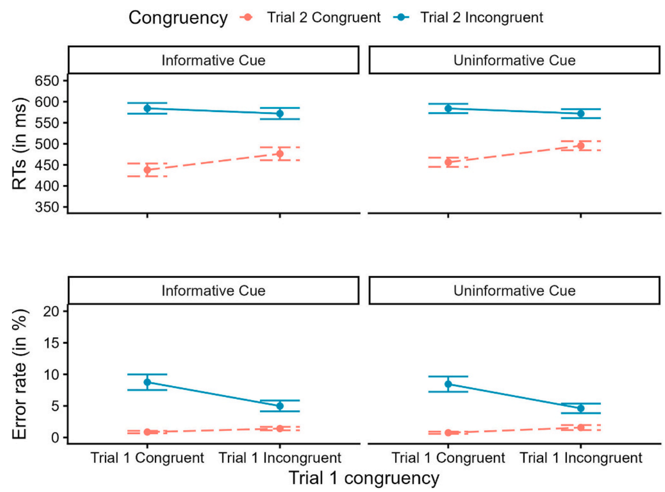

Fig. A2. Experiment 2: Descriptive statistics for Trial 2 performance. Error bars represent the standard error of the mean.

A.3. Experiment 3

A.3.1. Trial 1 analyses

Descriptive statistics for Trial 1 performance are represented in Table A1. The pattern of results was similar to that of Experiments 1 and 2. A robust congruency effect was observed as indicated by the main effect of Trial 1 Congruency, $F(1, 51) = 614.48$, $p < .001$, $\eta_p^2 = 0.92$. Trial 2 Congruency had no impact on performance overall $F(1, 51) < 1$. Crucially however, these factors interacted, $F(1, 51) = 5.90$, $p = .019$, $\eta_p^2 = 0.10$, replicating again the emergence of a future-based CSE. Follow-up comparisons did not allow us to determine whether this pattern was driven by congruent or incongruent trials, but the numerical tendencies, as in Experiments 1 and 2, were for congruent trials to be faster when Trial 2 was incongruent vs. congruent (−4 ms), $t(51) = 1.36$, $p = .180$, $d_z = 0.19$, and for incongruent trials to be slower when Trial 2 was incongruent vs. congruent (4 ms), $t(51) = 1.97$, $p = .055$, $d_z = 0.27$.

In the error rates analyses, the main effect of Trial 1 Congruency was the only one to reach significance, $F(1, 51) = 76.64$, $p < .001$, $\eta_p^2 = 0.59$. The interaction between Trial 1 Congruency and Trial 2 Congruency was marginal, $F(1, 51) = 3.34$, $p = .073$, $\eta_p^2 = 0.06$, reflecting the fact that, numerically, the error rate increased in congruent trials when Trial 2 was incongruent vs. congruent, (−0.7%), whereas Trial 2 congruency had virtually no impact on incongruent trials (0.2%).

A.3.2. Trial 2 analyses

Descriptive statistics for Trial 2 performance are represented in Fig. A3. The main effects of Trial 2 Congruency, $F(1, 51) = 568.81$, $p < .001$, $\eta_p^2 = 0.92$, and Trial 1 Congruency, $F(1, 51) = 13.73$, $p < .001$, $\eta_p^2 = 0.21$, indicated that performance was overall faster when a congruent stimulus was present in either trial. These effects interacted indicating the occurrence of a significant CSE, $F(1, 51) = 94.29$, $p < .001$, $\eta_p^2 = 0.64$. The main effect of Block Type was only marginally significant, $F(1, 51) = 3.79$, $p = .057$, $\eta_p^2 = 0.07$, indicating a trend for overall cueing benefits. This effect was significantly modulated by Block Type, $F(1, 51) = 8.40$, $p = .006$, $\eta_p^2 = 0.14$. While responses were faster when a congruent cue was provided (20 ms), $t(51) = 2.44$, $p = .018$, $d_z = 0.34$, such an improvement was much smaller (and not significant) in incongruent trials (3 ms), $t(51) < 1$.

In the error rates we again found the main effects of Trial 2 Congruency, $F(1, 51) = 127.09$, $p < .001$, $\eta_p^2 = 0.71$, and Trial 1 Congruency, $F(1, 51) = 12.33$, $p < .001$, $\eta_p^2 = 0.19$. These effects interacted significantly indicating the occurrence of the CSE, $F(1, 51) = 8.60$, $p = .005$, $\eta_p^2 = 0.14$. Finally, the main effect of Block Type was significant, $F(1, 51) = 4.45$, $p = .040$, $\eta_p^2 = 0.08$. Surprisingly, the effect indicated that more errors were committed in informative-cue blocks (5.2%) compared to uninformative-cue blocks (4.1%). Contrasted with the regular cueing effect in the RT results, this fact seems to suggest that congruency cues provoked a speed-accuracy tradeoff in this specific experiment.

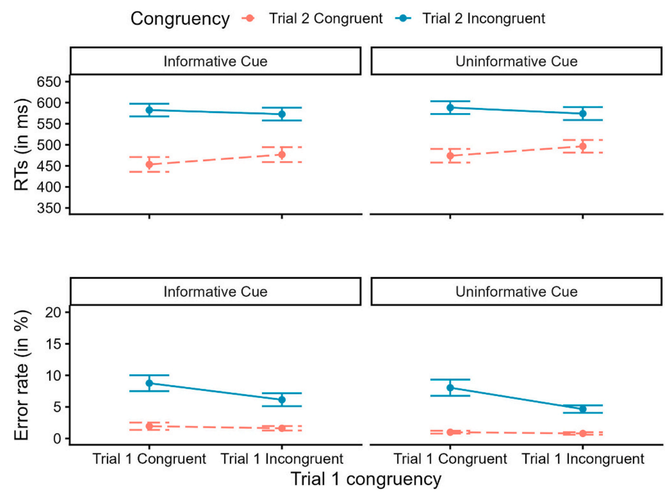

Fig. A3. Experiment 3: Descriptive statistics of Trial 2 performance. Error bars represent the standard error of the mean.

Appendix B. Block-order analysis

In the present study, informative- and uninformative-cues were presented in separate blocks, similar to the design employed by Bugg and Smallwood (2016). Although blocked designs have been described as being more effective in eliciting congruency-cue benefits (Jiménez et al., 2021), one limitation of this set-up is that participants performing the informative-cue blocks first may approach the task differently from those starting with uninformative-cue blocks, for a variety of reasons. For example, it has been proposed that it is not possible to regulate cognitive control based on instructions alone, and this ability needs to be developed through task practice (Braem et al., 2024). It is therefore possible that cue exploitation is more effective among participants starting with the uninformative-cue condition, as they accumulate practice with the task before undergoing informative-cue blocks, in which control needs to be adapted based on instructions. Because we hypothesise that the future-based CSE is related to cue exploitation, these participants may also display the strongest future-based CSE. Alternatively, it is possible that participants starting with the informative-cue condition would display the strongest cueing benefits and future-based CSE. Cued-first participants may in fact exploit cues more strongly, as they are less fatigued, and more engaged in the task at first. Furthermore, uncued-first participants may be discouraged in using the congruency cues as they experienced the feasibility of the task even without having to rely on cues.

To explore potential differences between groups, in the present analysis we included Block Order (Informative-first, Uninformative-first) as a between-subject factor. However, because any interaction between Block Order and Block Type (Informative cue, Uninformative cue) confounds order effects with practice effects (e.g., participants starting with informative-cue blocks will perform worse in these blocks due to performance improvement throughout the task), we decided to only assess whether the future-based CSE in informative-cue blocks differs between groups, without including uninformative-cue blocks in the analyses. To this aim, we conducted a 2 × 2 × 2 mixed ANOVA, with Trial 1 Congruency (congruent, incongruent), Trial 2 Congruency (congruent, incongruent) as within-subjects factors, and Block Order (informative-first, uninformative-first) as a between-subjects factor.

B.1. Results

In the RT analyses, we observed a main effect of Block Order, $F(1, 154) = 6.17$, $p = .014$, $\eta_p^2 = 0.04$, indicating faster performance for participants starting with uninformative blocks. In addition, as also reported in the main text, we found a significant main effect of Trial 1 Congruency, $F(1, 154) = 1661.97$, $p < .001$, $\eta_p^2 = 0.92$, and an interaction between Trial 1 Congruency and Trial 2 Congruency, $F(1, 154) = 19.64$, $p < .001$, $\eta_p^2 = 0.11$, indicating the emergence of the future-based CSE. Most crucially however, this interaction was significantly modulated by Block Order, $F(1, 154) = 4.67$, $p = .032$, $\eta_p^2 = 0.03$. We therefore assessed the future-based CSE separately for each group. While Trial 1 Congruency interacted with Trial 2 Congruency in the group starting with uninformative cues, $F(1, 78) = 27.01$, $p < .001$, $\eta_p^2 = 0.26$, the future-based CSE was not significant in the group starting with informative cues, $F(1, 76) = 2.07$, $p = .154$, $\eta_p^2 = 0.03$.

In the error rates analyses, as reported in the main text, we observed a main effect of Trial 1 Congruency, $F(1, 154) = 270.25$, $p < .001$, $\eta_p^2 = 0.64$, indicating the classic congruency effect, and a main effect of Trial 2 Congruency, $F(1, 154) = 9.41$, $p = .003$, $\eta_p^2 = 0.06$, indicating that performance was more error-prone when the next trial was cued to be incongruent. Furthermore, Block Order interacted with Trial 1 Congruency, $F(1, 154) = 6.81$, $p = .010$, $\eta_p^2 = 0.04$, with larger congruency effect in the uninformative-cue first group (9.5%), than in the informative-cue first group (5.6%). Finally, Trial 1 Congruency interacted with Trial 2 Congruency, $F(1, 154) = 6.26$, $p = .013$, $\eta_p^2 = 0.04$, indicating the emergence of the future-based CSE. Crucially, this effect was not modulated by Block Order, $F(1, 154) = 1.32$, $p = .252$, $\eta_p^2 < 0.01$, indicating that the future-based CSE did not significantly differ between groups.

B.2. Discussion

The presented analyses show both commonalities and differences between participants starting with informative- and uninformative-cues. Although the error rate analyses show that the future-based CSE emerges equally in both groups, confirming the robustness of this effect, the RT results suggest that starting with the uninformative condition facilitates prospective control adaptation. Although the present data do not allow us to pinpoint which factors may drive this difference, our results are consistent with the idea that instruction-based control adaptation requires a good deal of experience with the task to be successfully achieved (Braem et al., 2024). However, our conclusions are limited by the fact that the block order design does not allow us to investigate changes in cue exploitation, as performance in informative-cue and uninformative-cue blocks would be crucially confounded with practice. Future studies employing a between-subjects design may be fruitful in exploring the question of how experience interacts with cue exploitation and future-driven control adaptation.

Appendix C. Plot of transformed error rates

In the present study the analyses of error rates were performed following the arcsine-squared root transformation (Laurencelle & Cousineau, 2023), as indicated in the pre-registration protocols. However, in the main text we plot untransformed error rates to give a more intuitive sense of the absolute number of errors in our experiments. For completeness, here we plot the transformed error rates.

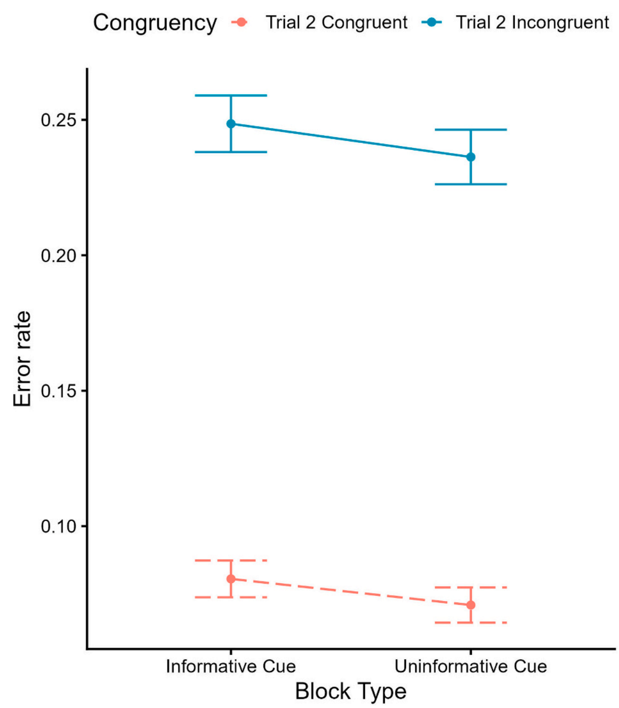

Fig. A4. Aggregated data analysis: Descriptive statistics of Trial 1 arcsine-squared root error rates. Error bars represent the standard error of the mean.

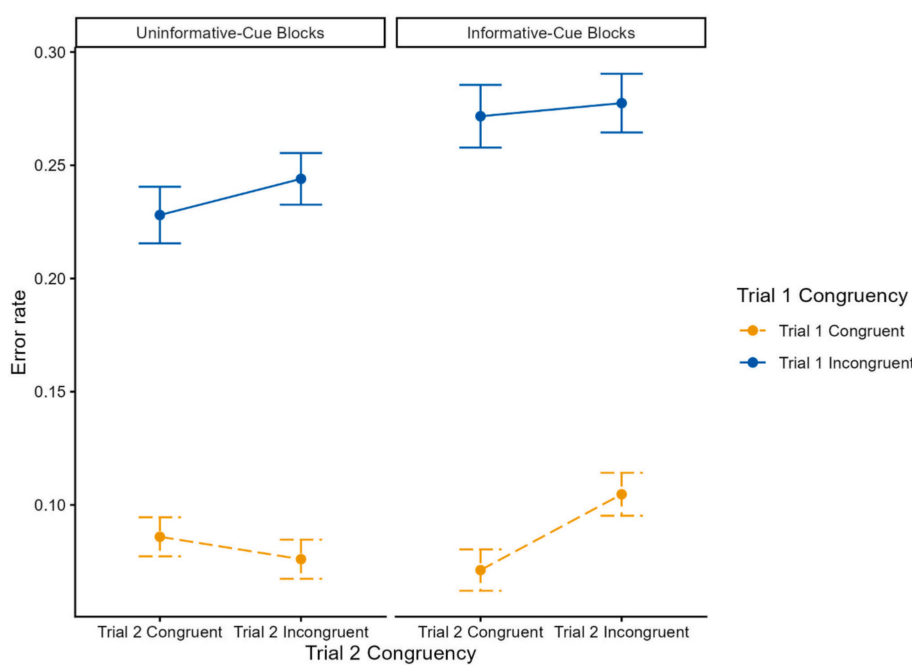

Fig. A5. Aggregated data analysis: Descriptive statistics of Trial 2 arcsine-squared root error rates. Error bars represent the standard error of the mean.

Data availability

Raw data and analyses scripts can be publicly accessed at: https://pasa.psycharchives.org/reviewonly/b2f154ebfa46e34fd2df75486dff62ae016c2abfc1d2678bf18457af248618da. Pre-registration protocols are publicly available at: https://aspredicted.org/rgj3-fh73.pdf and https://aspredicted.org/8fyy-9v9x.pdf

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