Parametric control of distractor-oriented attention

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Abstract

Traditional models of cognitive control account for a host of classic findings, but these classic tasks have limited our ability to test a broader range of model predictions. In particular, such models predict that control should vary parametrically in response to cognitive demands and that control adjustments should be targeted towards task-relevant stimulus features. We developed a task to probe these predictions across two experiments. Participants responded to one dimension of a stimulus while ignoring the other, and we parametrically varied the conflict between those dimensions and the predictability of this conflict across trials. We found that control adjustments (1) varied parametrically in response to cognitive demands, (2) were sensitive to the predictability of those demands, and (3) were primarily targeted towards task-irrelevant dimensions. These results raise interesting questions about the structure of cognitive control and demonstrate the utility of rich tasks for constraining model predictions.

Keywords: cognitive control; attention; conflict adaptation

Introduction

Cognitive control is vital for adaptive behavior, allowing the brain to balance the consistency of automatic behavior against the flexibility to rapidly perform arbitrary tasks (Miller & Cohen, 2001). Influential models of cognitive control have proposed supervisory processes that parametrically adjust the strength of task-relevant information based on conflict or (dis)utility (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Shenhav, Botvinick, & Cohen, 2013). While these models have successfully explained a host of classic findings in executive control, the evidence from these classic tasks is limited in its ability to constrain models of control. In this experiment, we sought to test several key assumptions of cognitive control using enriched tasks that can better discriminate between different model architectures.

The first feature of control models that has been virtually untested is the parametric nature of adjustments to control. Control adjustments are often examined in reaction to response conflict, but existing paradigms typically vary such conflict in an all-or-none fashion (i.e., stimulus dimensions activate only one response or they activate responses that are fully congruent or fully incongruent). Researchers have studied more granular control adjustments over longer timescales, for instance by varying the overall proportion of incongruent trials at the list level (Logan & Zbrodoff, 1979; Bugg, Jacoby, & Toth, 2008), however parametric manipulations at the single-trial level remain largely unexplored. As a result of this methodological gap in the literature, little is known about how the intensity of control changes when response congruence varies parametrically. A secondary benefit to parametric congruence is that it allows participants to more accurately track changes in congruence over trials, providing clearer evidence for learning-based adjustments (Jiang, Beck, Heller, & Egner, 2015).

The second feature of control models that we sought to test was the assumption that control primarily acts to enhance attention towards targets ('target-oriented' control; Botvinick et al., 2001; Egner, 2007). This assumption is poorly constrained by most studies of response conflict, as they typically only vary the strength of the distractor dimension, and not the target dimension. As a result, existing data cannot distinguish between conflict-related control adjustments that are primarily oriented toward targets, distractors, or both.

To address these gaps in the literature, we developed a novel cognitive control task that varies the strength in the target and/or distractor dimensions of a stimulus, resulting in fine-grained variation in response congruence. We also varied the predictability of this congruence, in order to measure how participants learn to control attention. We found that participant's performance depended on both parametric task demands and parametric control adjustments. In periods when distractor congruence was highly predictable, participants became more sensitive to distractor information. Finally, we found that participants primarily controlled their attention towards distractor dimensions, counter to the predictions of prominent cognitive control models. These experiment demonstrate the need for richer cognitive control tasks that can better distinguish between models of executive functioning.

Experiment 1

Experiment 1 sought to test (1) whether there is a parametric relationship between performance and response congruence; (2) whether participants parametrically adjust control based on recent task demands; and (3) how these control adjustments depend on the learned task demands over longer timescales.

Method

Participants Fifty-eight individuals participated in Experiment 1 for course credit or pay (Mean(SD) age = 20.9(2.6);

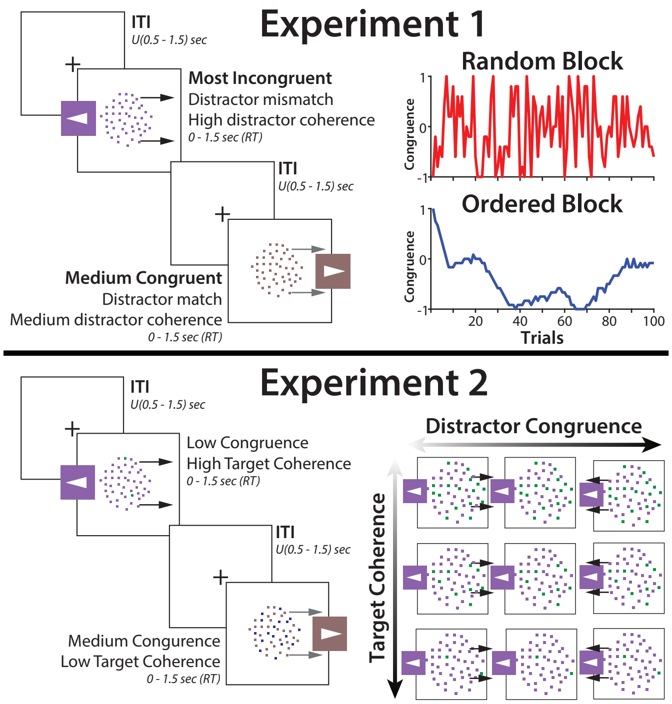

Figure 1: Top Left: In Experiment 1, participants responded to the color and ignored the motion of an array of pseudo-randomly moving dots. Motion coherence induced variable levels of congruence across dimensions. Top Right: Participants performed blocks in which the congruence changed randomly (red) or predictably (blue). Bottom Left: In Experiment 2, both the color and motion dimensions had variable coherence. Bottom Right: These color and motion dimensions were orthogonal

41 females). All participants across all experiments provided informed consent in compliance with our University's Institutional Review Board.

Parametric Conflict Task We developed a parametric version of a previous Simon-like conflict task (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011). On each trial, participants viewed an array of moving dots, presented in one of four colors (see Figure 1). Participants were instructed to press either the left or right key associated with the color of the dots. Each keys was mapped to two possible colors. The direction of the dot motion (leftward or rightward) was task-irrelevant and could be consistent with the response hand for the correct color response (*congruent* trials) or it could be inconsistent with this response hand (*incongruent* trials). To avoid feature priming (Hommel, Proctor, & Vu, 2004), colors did not repeat on adjacent trials.

Uniquely in this experiment, we parametrically varied the *degree* of response congruence on a given trial by varying the coherence of the dot motion (the % of dots moving in a given direction). Congruence was evenly sampled between 100% coherent congruence and 100% coherent incongruence, and was treated as a continuous variable in statistical analyses.

To maintain the salience of the motion dimension throughout the session, participants alternated between blocks of the task above (*color-response* trials) and blocks where participants were instructed to instead indicate the direction of motion (*motion-response* trials; cf. Schneider & Shiffrin, 1977). Mirroring color-response trials, motion coherence was held constant (maximal) during motion-response blocks, while color coherence (the proportion of one color vs. another) was varied across trials.

Procedure Participants first performed 100 motion-only training trials (0% coherent color) and 100 color-only training trials (0% coherent motion) to learn the stimulus-response mappings. During the main experiment, participants performed two types of trial blocks. During *Random* blocks, the distractor congruence varied randomly from trial-to-trial. During *Ordered* blocks, congruence linearly increased and decreased in a predictable manner (see Figure 1).

Variants Data for Experiment 1 incorporate several similar versions of this task. The main differences across versions was the number of congruence levels (mean(range) = 13.5(11-15) levels for Random blocks, mean(range) = 15.4(11-25) levels for Ordered blocks), as well as the number of trials in each block type (mean(range) = 469(300-700) for Random blocks, mean(range) = 643(300-800) for Ordered blocks). We did not find significant differences in performance across versions, nor interactions between task version and our effects of interest, and so our analyses collapse across these versions. Importantly, versions only differed in ways that should produce random rather than systematic error, potentially making our positive findings more conservative.

Results

All analyses were performed using linear mixed effects modelling in MATLAB (lmefit and glmefit). The dependent variables across analyses were log-transformed reaction time (RT) and accuracy. All models included a 'maximal' random effects structure at the participant level and intercept terms (not reported). All analyses excluded trials with RTs faster than 200ms, RT analyses excluded incorrect trials, and adaptation analyses required the previous trial to also be accurate and have an RT longer than 200ms. We estimated the effective degrees of freedom with the Satterthwaite approximation for RT models, and used $(n_{Participants} - n_{Predictors})$ for accuracy models. Models were compared on the basis of Akaike Information Criterion (AIC), a goodness-of-fit metric that penalizes model complexity.

Parametric Within-trial Interference Effects Within Random blocks, we found that RT and accuracy varied linearly with our parametric manipulation of congruency (see Figure 2; Table 1). As confirmation that performance varied parametrically across congruence levels, we found that a model that treated congruence as a single continuous variable

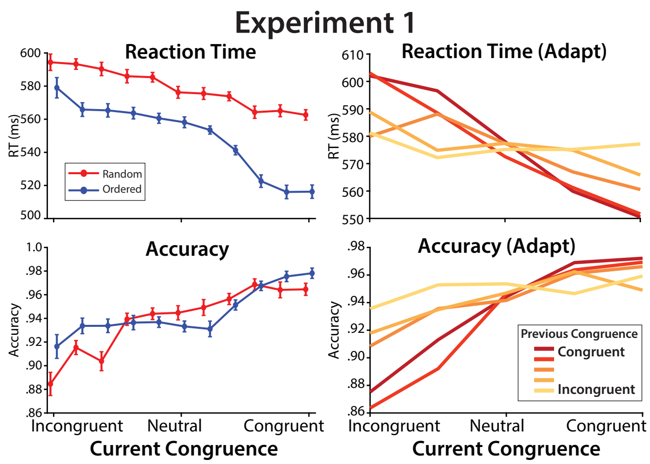

Figure 2: Left: RT (top) and accuracy (bottom) linearly depended on the degree of distractor congruency, moreso in Ordered blocks (blue) than Random blocks (red). Right: The influence of congruence on RT (top) and accuracy (bottom) linearly depended on the previous level of congruence. In all graphs, error bares indicate within-participant SEM.

fit better than a model that treated congruence as a binary variable (congruent vs. incongruent) and a model with separate congruence slopes for trials with target-compatible vs. target-incompatible coherence levels (i.e., levels of congruency vs. levels of incongruency).

Table 1: Parametric Congruence (Exp 1)
performance $\sim$ *congruence*

DV	IV	β	*t*(df)	*p*
logRT	cong	-0.030	-8.0(60)	4.5e-11
accuracy	cong	0.74	9.6(57)	8.2e-14

Parametric Between-trial Adaptation Effects These initial analyses suggest that we were successful in parametrically varying cognitive demands across trials. To test whether this manipulation in turn led to parametric variations in the strength of *control* allocated to the task, we tested how participants' performance changed after a trial that was more or less demanding (i.e., the 'Gratton' or conflict adaptation effect; Gratton, Coles, & Donchin, 1992). Consistent with previous findings of such adaptation effects, we found that RT and accuracy on the current trial was predicted by the interaction between the congruence of the current and previous trials, with stronger congruence on one trial predicting stronger distractor sensitivity on the next trial. Importantly, these adaptation effects were present over and above the effect of current-trial congruency and – like those within-trial effects – *also* varied parametrically (see Figure 2; Table 2).

Interestingly, we found that the previous trial's congruence alone had little influence on current-trial performance, instead modulating the degree to which performance was facilitated by or interfered with by the distractor's current congruence. When the distractor was previously more congruent (i.e., more associated with a correct response), participants incorporated more distractor information into their response; when the previous distractor was more incongruent, participants' performance was virtually independent of the current degree of congruence.

Table 2: Conflict Adaptation (Exp 1)
$performance_t \sim congruence_t * congruence_{t-1}$

DV	IV	β	*t*(df)	*p*
logRT	cong_t	-0.030	-8.1(59)	4.2e-11
	cong_{t-1}	9.1e-4	0.33(58)	.75
	cong_t:cong_{t-1}	-0.028	-6.2(56)	7.5e-08
accuracy	cong_t	0.69	9.3(57)	5.0e-13
	cong_{t-1}	-.099	-1.9(57)	.06
	cong_t:cong_{t-1}	0.47	6.3(56)	4.9e-8

Influence of Demand Predictability on Control Allocation To determine how control adjustments changed when task difficulty was highly predictable, we compared congruence effects across Random and Ordered blocks (see Figure 2; Table 3). We predicted that participants would match their control allocation to local demands, resulting in weaker congruence effects during Ordered blocks, and better overall performance. While we found that participants were overall faster in Ordered block, they were less accurate, and we found that RTs were in fact more influenced by congruence during Ordered relative to Random blocks.

Table 3: Block Effects (Exp 1)
performance $\sim$ *block*(congruence + coherence)*

DV	IV	β	*t*(df)	*p*
logRT	block	-0.033	-4.0(57)	2.2e-4
	cong	-0.030	-8.0(59)	5.7e-11
	coh	6.1e-4	-0.14(53)	0.89
	block:cong	-0.023	-4.6(59)	2.3e-5
	block:coh	-0.035	-4.7(55)	1.9e-5
accuracy	block	-0.37	-3.9(57)	2.9e-4
	cong	0.69	9.5(57)	2.8e-13
	coh	-0.22	-2.2(57)	.031
	block:cong	-0.016	-0.18(56)	.86
	block:coh	0.91	6.4(56)	3.9e-8

In addition to the block difference in congruence, we found that participant's performance was enhanced when there was greater distractor coherence in Ordered blocks, regardless of whether the distractor was congruent or incongruent with the target. This is consistent with participants learning to use distractor information, i.e., responding in the same or opposite direction of the distractor. In sum, the influence of distractors on choice was enhanced when the they could be used to make accurate responses, with a stronger bias towards distractor-congruent trials. Interestingly, these effects were present in spite of most participants reporting that they had not noticed the predictability manipulation.

Relative Automaticity of Motion vs. Color Processing We designed our task under the assumption that the response compatibility of the motion dimension would make responding to it more automatic than responding to the color dimension. To validate this assumption, we tested whether these dimensions would interfere with one another asymmetrically (Schneider Shiffrin, 1977). Consistent with this prediction, we found that when participants were instructed to respond based on the motion dimension (rather than color), we did not observe any interference effects associated with the congruency of the color dimension (logRT: $b = 5.9e{-4}$, $p = .33$; accuracy: $b = 0.031$ $p = .088$; compare to Table 1), in stark contrast with the results reported above for color-response trials.

Discussion

Experiment 1 sheds new light on how attention is parametrically controlled based on local and long-term task demands. First, we observed that performance depends on the continuous degree of interference, supporting participants' ability to track parametric task demands and control their attention accordingly.

The second major observation from this experiment was that participants parametrically adjust their sensitivity to distracting information based on the degree of interference they previously experienced. Interestingly, we found that participants' performance was not strongly modulated by previous congruence per se, but that the previous congruence influenced distractor sensitivity. This is largely consistent with traditional conflict adaptation effects, which are commonly attributed to a controlled increase in attention towards targets following incongruent trials, which reduce the influence of distractors as a secondary effect (Botvinick et al., 2001; Egner, 2007). In contrast to these models' predictions, the effect of previous congruence was evaluated when the current congruence was neutral (0% coherence), the situation where target enhancement should should be most obvious. Our results are more consistent with changes in distractor processing than target processing.

Finally, we found that under conditions of high predictability, participants increased their attention towards distractors when they were informative (i.e., provided coherent evidence for or against a response), but with a strong bias towards distractors that provided target-congruent evidence. This observation is consistent with the literature on the proportion congruency effect (i.e., weaker congruency effects in blocks of majority-incongruent trials; Logan & Zbrodoff, 1979), originally attributed to participants' learning the predictive value of different stimulus dimensions. This strict learning account does not predict a bias towards distractor-congruent information, making our results more compatible with models that combine learning to weight different cues with adjustments based on the recent history of conflict (Jones, Cho, Nystrom, Cohen, & Braver, 2002).

In sum, these results suggest that participants controlled their attention towards the distracting dimension based on both the learned value of this cue and a bias towards congruent distractors. However, this preliminary evidence for distractor-oriented control is limited by the standard convention of only manipulating distractor congruence. To better isolate control adjustments towards targets and distractors, in Experiment 2 we manipulated the coherence of each dimension to better measure where participants controlled their attention.

Experiment 2

Experiment 2 sought to further characterize the targets of control adjustment in this task. In particular, we examined the degree to which participants adjust their attention towards targets and distractors in response to the demands associated with each dimension. We measured this by independently manipulating the coherence of both the target and distractor dimensions. By 'tagging' these different stimulus dimensions, we sought to determine where participants adjust attention. The traditional target-oriented attention account makes two key predictions: first, if distractor sensitivity is a byproduct of control towards targets (e.g., due to lateral inhibition; Botvinick et al., 2001), then the influence of target and distractor information should strongly interact within a trial. Secondly, we should find that trial-to-trial adjustments to control should primarily influence the sensitivity to the target dimension.

Method

Participants Thirty-three individuals participated in Experiment 2 for course credit or pay (Mean(SD) age = 18.9(0.45); 24 females).

Task & Procedure This task was similar to Experiment 1, except that we varied the coherence of both the distractor (motion) and target (color) dimensions. As in Experiments 1, motion coherence varied from 100% leftward to 100% rightward (11 levels of congruence). Target coherence (i.e., the proportion of dots whose color indicates a leftward or rightward response) varied from 65% to 95% (11 levels of coherence). Participants only performed Random blocks (1200 color-response trials with interleaved motion-response blocks, as in Experiment 1), with the target coherence and distractor congruence independently sampled on every trial.

Results

We used the same linear mixed effects regression approach here as we did in Experiment 1. Target coherence was mean-centered within participants to aid in interpretability.

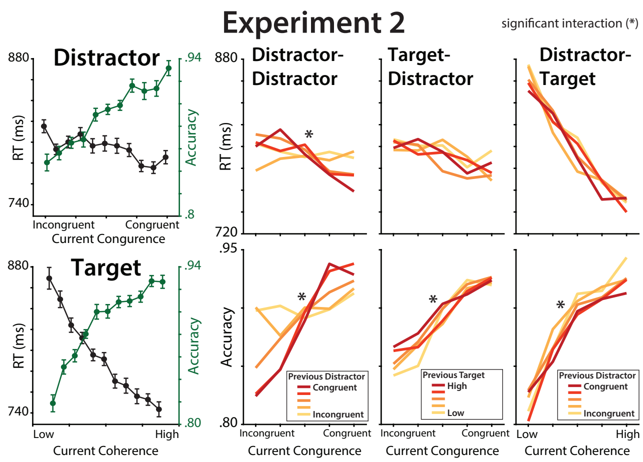

Figure 3: Left: RT (black) and accuracy (green) linearly depended on both distractor congruence (top) and target coherence (bottom). Right: Conflict adaptation was stronger and more consistent for the distractor dimensions. Asterisks indicate significant interactions.

Within-trial Effects of Target and Distractor Information As predicted, we found that performance improved with both greater target coherence and greater distractor congruence within each trial (see Figure 3; Table 4). Interestingly, these dimensions influenced performance largely independently of one another. The interaction between target and distractor information had a significant effect on accuracy ($p<0.01$) but not RT ($p=0.79$), However, relative to models with only main effects, models that included these interaction terms did not improve overall model fit for either RT (Δ AIC = 14) or accuracy (Δ AIC = 0.80).

Table 4: Target & Distractor Within-Trial (Exp 2)
*performance ~ (distractor * target)*

DV	IV	β	*t*(df)	*p*
logRT	dist	0.031	-7.1(32)	4.6e-8
	targ	-0.20	-12(32)	1.2e-13
	dist:targ	-0.0038	-0.26(53)	.79
accuracy	dist	-0.46	-8.6(32)	8.2e-10
	targ	2.3	11(32)	6.1e-12
	dist:targ	-0.44	-2.8(31)	.0094

Target- vs. Distractor-Dependent Adaptation While both target coherence and distractor congruence influenced participants' performance within a given trial, our primary interest was how participants adjust attention from trial to trial. To investigate this, we measured how participants' sensitivity to target and distractor information changed as a function of the previous trial difficulty. The prediction of traditional target-oriented accounts is that previous task demands will most strongly change sensitivity to the target dimension.

We found that the previous distractor congruence strongly influenced participants' sensitivity to the current distractor congruence, replicating our parametric conflict adaption results from Experiment 1 (see Figure 3; Table 5). In contrast to traditional models, we found that the previous distractor had an inconsistent influence over participants' sensitivity to the current target coherence, appearing in the domain of RT but not accuracy. Interestingly, the previous trial's congruence had opposing effects on targets and distractors: more incongruent trials were followed by weaker sensitivity to distractors and stronger sensitivity to targets, albeit with substantively weaker adjustments to target sensitivity.

Table 5: Distractor-Dependent Adaptation (Exp 2)
$performance_t \sim distractor_{t-1} * (distractor_t + target_t)$

DV	IV	β	*t*(df)	*p*
logRT	dist_{t-1}	-8.9e-5	-0.03(94)	.97
	dist_t	-0.031	-7.2(33)	4.6e-8
	targ_t	-0.20	-12(32)	3.4e-13
	$\text{dist}_{t-1}\text{:dist}_t$	-0.028	-6.5(191)	7.3e-10
	$\text{dist}_{t-1}\text{:targ}_t$	-0.012	-0.26(406)	.39
accuracy	dist_{t-1}	-0.07	-2.1(32)	.047
	dist_t	0.41	8.1(32)	3.4e-9
	targ_t	2.3	11(32)	3.2e-12
	$\text{dist}_{t-1}\text{:dist}_t$	0.46	7.6(31)	1.5e-8
	$\text{dist}_{t-1}\text{:targ}_t$	-0.39	-2.1(31)	.043

We also tested a model where the previous target coherence could influence sensitivity towards the current target and distractor (see Figure 3; Table 6). We found, again, no evidence in reaction time that previous target coherence influenced the current target or distractor sensitivity. However, in accuracy we found that weaker previous trial target coherence predicted a stronger reliance on distractor information on the next trial, with no change to the reliance on target information.

Table 6: Target-Dependent Adaptation (Exp 2)
$performance_t \sim target_{t-1} * (distractor_t + target_t)$

DV	IV	β	*t*(df)	*p*
logRT	dist_t	-0.031	-7.2(32)	3.0e-8
	targ_t	-0.20	-12(32)	3.7e-13
	targ_{t-1}	-0.011	-0.98(32)	.34
	$\text{targ}_{t-1}\text{:dist}_t$	-0.0028	-0.18(37)	.86
	$\text{targ}_{t-1}\text{:targ}_t$	0.038	0.73(43)	.47
accuracy	dist_t	0.42	8.5(32)	1.2e-9
	targ_t	2.3	11(32)	2.9e-12
	targ_{t-1}	0.12	1.1(32)	.28
	$\text{targ}_{t-1}\text{:dist}_t$	-0.41	-2.5(31)	.012
	$\text{targ}_{t-1}\text{:targ}_t$	-0.12	-0.22(31)	.83

Overall, target- and distractor-dependent adaptation seem to support a similar mechanism, in which the response-relevance of a dimension modifies the extent to which it is subsequent used for choice, with a strong bias towards modifying the distractor dimension. When the target dimension is incongruent with the response, participants are subsequently more influenced by target and less influenced by distractors. When the target provided weak evidence for the response, participants were subsequently more sensitive to distractors.

Discussion

Experiment 2 replicated the within- and between-trial congruence effects observed in Experiment 1. Critically, Experiment 2 also provided unique evidence in favor of distractor-oriented attentional control in this task.

Within trials, we found that both target and distractor information influenced task performance, there were only weak interactions across dimensions. This runs counter to the predictions from models that posit competitive interactions between the processing of targets and distractors, in which distractor sensitivity changes as a byproduct of target-oriented control (Botvinick et al., 2001; Egner, 2007).

Across trials, we found that adjustments to control primarily acted on distractors, in contrast with traditional models of conflict adaptation. When the previous trial was difficult, participants suppressed distractors if the difficulty was due to incongruent distractors, and enhanced distractors if the difficulty was due to low-coherence targets. It is notable that the latter effect of distractor enhancement appeared to be specific to accuracy, whereas the suppression effect was observed in both speed and accuracy. Whether these reflects different forms of control adjustment (e.g., related to evidence accumulation versus response threshold) demands further investigation with models that can distinguish these processes (e.g., the drift diffusion model).

In addition to these distractor adjustments, we also observed adjustments to target sensitivity in one condition (distractor-dependent adaptation effects in accuracy). However these adjustments to target processing were very subtle, compared to the strong and reliable adaptation effects observed for the distractor dimension, and could plausibly represent a byproduct of these dominant adjustments to distractor processing.

General Discussion

We developed a novel task aimed at examining parametric adjustments of control towards targets and distractors. Across our two experiments, we found consistent evidence that participants parametrically controlled their attention towards distractors based on the recent history of task demands. In Experiment 1, we found that participants adjusted their sensitivity to distractor congruence based on both whether distractors could predict the accurate response, alongside the bias towards congruency predicted by conflict monitoring. In Experiment 2, we narrowed down the sources and targets of this process of control adaptation. We found that participants adjusted attention towards distractors much more than they did towards targets. Together, these results provide strong confirmation for many aspects of existing models of cognitive control, while challenging models that propose unbiased or target-oriented attentional control.

Our experiments leave open the question of why participants would be biased towards distractor-oriented attention. One reason for this asymmetry may due to a primacy for inhibition in cognitive control, exemplified by the well-characterized 'hyperdirect' control of striatal decision-making (Wiecki & Frank, 2013) and the common inhibition factor found across several executive control tasks (Friedman & Miyake, 2017). This may describe why it is easier to (dis)inhibit attention towards distractors, rather than enhance attention to targets, but offers little explanation for *why* there is this preference for inhibition. Another reason for our asymmetry may be that our distracting motion dimension, like many distractors, is easier to control because of its salience. Insofar as attention control requires some form of feature selection, it may be easier to select a distractor's stimulus features to act upon. Finally, this experiment cannot rule out that there is something about motion *per se* that makes it easier to control. Future experiment should test the robustness of these results across multiple stimulus domains and forms of congruence before making more provocative conclusions about the nature of cognitive control.

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