Psychological Research (2016) 80:16–33
DOI 10.1007/s00426-014-0638-5

ORIGINAL ARTICLE

The next trial will be conflicting! Effects of explicit congruency pre-cues on cognitive control

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Received: 25 August 2014 / Accepted: 5 December 2014 / Published online: 19 December 2014

Abstract The dual mechanisms of control account proposed a role for proactive and reactive mechanisms in minimizing or resolving interference in conflict tasks. Proactive mechanisms are activated in advance of stimulus onset and lead to preparatory biasing of attention in a goal-directed fashion. Reactive mechanisms are triggered post-stimulus onset. Using an explicit, trial-by-trial pre-cueing procedure in a 4-choice color-word Stroop task, we investigated effects of congruency pre-cues on cognitive control. Under conditions of stimulus uncertainty (i.e., each word was associated with multiple, equally probable responses), pre-cue benefits were observed on incongruent trials when cues were 100 % valid but not when they were 75 % valid. These benefits were selectively found at the longest cue-to-stimulus interval (2,000 ms), consistent with a preparation-dependent proactive control mechanism. By contrast, when a reactive strategy of switching attention to the irrelevant dimension to predict the single correlated response was viable, pre-cue benefits were observed on incongruent trials for all cue-to-stimulus intervals including the shortest that afforded only 500 ms to prepare. The findings (a) suggest a restricted role for the preparation-dependent biasing of attention via proactive control in response to explicit, trial-by-trial pre-cues while (b) highlighting strategies that lead to pre-cue benefits but which appear to reflect primarily reactive use of the information afforded by the pre-cues. We conclude that pre-cues, though available in advance of stimulus onset, may stimulate proactive or reactive minimization of interference.

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Introduction

It has long been established that performance is enhanced when participants are provided with explicit cues about an upcoming stimulus. In a classic study, Posner, Snyder and Davidson (1980) showed that simple response times were speeded when a stimulus appeared in a validly cued location and slowed when it appeared in an invalidly cued location. In other words, the detection of the stimulus was facilitated when experience matched expectations that were generated in advance of the stimulus, and disrupted when experience conflicted with expectations (cf. Posner & Snyder, 1975). Of interest in the present study is the question of whether advance expectations influence cognitive control of interference, in particular, the processes used to bias attention in favor of goal-relevant information and away from irrelevant information.

Conflict paradigms such as color-word Stroop are frequently employed to assess cognitive control of interference. Color-naming times are typically slowed on incongruent (i.e., RED in blue ink) as compared to congruent (i.e., BLUE in blue ink) trials (MacLeod, 1991; Stroop, 1935). The slowing on incongruent trials is often attributed to the conflict (interference) that arises when attention is drawn to the irrelevant word (e.g., Melara & Algom, 2003). Conflict-monitoring accounts assert that cognitive control is triggered reactively after a stimulus is presented in response to the detection of conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Blais, Robidoux, Risko, & Besner, 2007). An alternative account, the dual mechanisms of control (DMC) framework, proposes that cognitive control may be accomplished by either reactive or proactive mechanisms (Braver, Gray, & Burgess, 2007). Proactive control is a preparation-dependent process that involves the active maintenance of a goal representation (e.g., focus on color and ignore the word) prior to the occurrence of a target stimulus (and any conflict that arises). The advantage of proactive control, according to the DMC account, is the prevention or minimization of interference. However, because it is computationally more costly (i.e., utilizes resources such as glucose), its engagement is thought to be dependent on a high likelihood of reward, such as when cues reliably signal that interference is expected (Braver et al., 2007).

One line of research that is often cited as evidence for proactive control employs manipulations that alter global expectations by varying the proportion of congruent relative to incongruent trials across blocks (Logan & Zbrodoff, 1979; cf. proportion color-word manipulation of Tzelgov, Henik, & Berger, 1992; for reviews, see Bugg, 2012; Bugg & Crump, 2012). When conflict is frequent, as in a mostly incongruent list, there is less interference than when it is rare, as in a mostly congruent list (e.g., Kane & Engle, 2003; Lindsay & Jacoby, 1994; Logan, 1980; Logan, Zbrodoff, & Williamson, 1984; Lowe & Mitterer, 1982; West & Baylis, 1998; see also Gratton, Coles, & Donchin, 1992; Hommel, 1994; Toth, Levine, Stuss, Oh, Winocur, & Meiran, 1995; Wendt & Luna-Rodriguez, 2009 for the same pattern in other conflict paradigms). This pattern, referred to as the list-wide proportion congruence effect, is consistent with the possibility that proactive control is enhanced when interference is expected (i.e., in a mostly incongruent list), and neural activation patterns corroborate this view (DePisapia & Braver, 2006). However, recent studies have challenged this interpretation by demonstrating that reactive mechanisms (i.e., reactive control and/or prediction of highly associated responses) operating post-stimulus onset sometimes account for the effect (Blais & Bunge, 2010; Bugg, 2014, Experiments 2 and 3; Bugg, Jacoby, & Toth, 2008; but see Bugg, 2014, Experiments 1 and 4; Bugg & Chanani, 2011; Bugg, McDaniel, Scullin, & Braver, 2011b; Hutchison, 2011 for evidence of list-wide effects independent of reactive mechanisms; see Schmidt, 2013, 2014, for an alternative interpretation of list-wide effects based on temporal learning).

In addition, the typical list-wide proportion congruence manipulation does not permit one to determine the degree to which proactive control is operating based on explicit expectations of interference (but see Bugg, Diede, Cohen-Shikora, & Selmeczy, in press). Blais, Harris, Guerrero, and Bunge (2012) showed that participants' awareness of the list-wide proportion congruence manipulation (i.e., accuracy in indicating whether a particular block had more congruent or incongruent trials) was poor and unrelated to the magnitude of the list-wide proportion congruence effect. That is, those who were more aware did not tend to show larger effects. Blais et al. concluded that the effect likely reflects implicit adaptations such as learning regularities in each list (e.g., frequencies of particular trial types) and subconsciously adapting to them rather than an explicit strategy (but see Hommel, 2013, for discussion of the informativeness of such correlations for addressing the causal role of consciousness in control).[1]

A potentially more direct approach to exploring the role of explicit expectations in proactive control is to pre-cue the likelihood of interference via trial-by-trial congruency pre-cues. To the extent that participants can utilize such information to prepare proactive control, one should find evidence for pre-cue benefits in the form of better performance when pre-cues are available than when they are not. To date, only a few studies have employed this approach, and the findings leave open several theoretically important questions that we aim to address in the present study (for related literatures, see cued task-switching Stroop studies in which participants are cued to read words or name colors on a trial-by-trial basis, e.g., MacDonald, Cohen, Stenger, & Carter, 2000; see also Stroop studies in which participants are informed of the upcoming distractor word in advance of the stimulus; Chao, 2011; Dyer, 1974).

Explicit trial-by-trial pre-cueing effects

In the seminal study, Logan and Zbrodoff (1982) presented 100 % valid pre-cues (X or O for 100 ms) in a spatial Stroop task [e.g., the word ABOVE is presented in a location above (congruent) or below (incongruent) fixation] in which the participant's goal was to respond to the word. The pre-cue was presented 100, 200, 400, 600, 800, or 1,000 ms prior to the onset of the target Stroop stimulus. Participants were told that an X pre-cue indicated that the word and its position would correspond (i.e., a congruent trial) whereas an O pre-cue indicated that the word and its position would not correspond (i.e., an incongruent trial). Half of trials were congruent and half were incongruent. Performance in blocks in which the informative pre-cues were presented was compared to performance in matched blocks (i.e., also 50 % congruent) in which a neutral (non-informative) pre-cue was shown prior to

[1] Although a cross-experimental analysis was not reported by Logan and Zbrodoff (1979), consistent with the view of Blais et al. (2012), the magnitude of the list-wide proportion congruence effect appeared to be similar in Experiment 1 wherein participants were not explicitly informed about the proportion congruency of the list and Experiments 2 and 3 wherein they were.

each trial.[2] The key finding was that reaction times were faster in the informative pre-cue condition relative to the non-informative condition (i.e., a pre-cue benefit); this benefit was larger for congruent than incongruent trials (see also Correa, Rao, & Nobre, 2008 for a similar pattern in a flanker task using 100 % valid pre-cues), and for longer than shorter delays between the cue and the stimulus.

These findings appear to provide evidence for the trial-by-trial modulation of proactive control. However, an alternative explanation is possible given Logan and Zbrodoff's (1982) use of tasks that included only two possible stimuli and responses (see also Correa et al., 2008). When an incongruent pre-cue was shown, participants may have adopted the strategy of discriminating the location upon stimulus onset and producing the response that was opposite to that location (e.g., saying "below" when word is above fixation). In fact Logan and Zbrodoff concluded that participants were switching attention (to the irrelevant dimension) via this strategy. Importantly, this suggests that benefits due to information that is available in advance of a stimulus are not necessarily indicative of proactive control *a la* the DMC account—the benefits may accrue from a process that aligns more closely with the concept of a reactive mechanism in that the response to be predicted (by attending to the irrelevant dimension) can only be known after the stimulus is presented.

To potentially reveal proactive control, one must rule out the contributions of an attention-switching strategy on incongruent trials. Conditions of stimulus uncertainty permit one to do so (see Wühr & Kunde, 2008). Stimulus uncertainty refers to there being several equally probable responses that are correlated with the irrelevant dimension such that the reactive strategy of predicting the response by switching attention to the irrelevant dimension is ineffective. If participants can heighten proactive control (i.e., activate a goal representation prior to stimulus onset to facilitate biasing of attention in favor of the relevant dimension or away from the irrelevant dimension) when interference is expected, then pre-cue benefits should be found for incongruent trials even under conditions of stimulus uncertainty.

Goldfarb and Henik (2013) tested this prediction, and the findings were mixed. In Experiment 1, the pre-cue "X" validly signaled an incongruent stimulus and the pre-cue "O" validly signaled a neutral stimulus (a non-color word). Pre-cues were presented for 1,000 or 2,000 ms. Half of the trials within each block were preceded by a valid pre-cue whereas the other half were preceded by a "?" (i.e., a non-informative pre-cue), and 50 % of trials were incongruent and 50 % were neutral. There was no pre-cue benefit for incongruent stimuli nor was there a benefit for neutral stimuli. However, in Experiment 2, a selective pre-cue benefit was found for incongruent trials; the benefit was present when most trials within a block were neutral but not when most trials were incongruent. Features of the design such as stimulus uncertainty, the absence of congruent trials, nature of the pre-cues and pre-cue duration were identical to Experiment 1. This suggests that the differing findings were due to the proportion manipulation. Engagement of proactive control in response to congruency pre-cues may be most likely in contexts in which the global likelihood of conflict does not in and of itself trigger a maximal heightening of control (Goldfarb & Henik, 2013).

Current study

The current study further examined pre-cue benefits in 4-choice color-word Stroop tasks in which the global likelihood of conflict was not expected to lead to a maximal heightening of control (i.e., blocks were 50 % congruent). We identified three primary theoretical questions of interest: first, are pre-cue benefits preparation-dependent as would be expected if such benefits reflected use of proactive control *a la* the DMC account? Second, does preparation time have differing effects depending on whether conditions of stimulus uncertainty are present (Experiment 1) or are not present (Experiment 2) in a 4-choice task? In other words, might preparation time be especially important in designs that bias adoption of proactive control vs. an attention-switching strategy, respectively? Third, are pre-cue benefits dependent on use of pre-cues that are 100 % valid, and are there costs of cue invalidity (Experiment 3)?

To address these questions, we adopted the original design of Logan and Zbrodoff (1982) in which informative pre-cues were presented in one block and non-informative pre-cues were presented in a separate block (cf. Wühr & Kunde, 2008, for a similar design with the Simon task; Posner et al., 1980), and both blocks were 50 % congruent.[3] The informative and non-informative pre-cue conditions were equated save for the provision of explicit

[2] Logan and Zbrodoff's second experiment intermixed informative pre-cue trials and neutral (non-informative) trials within a block. A single informative pre-cue (the X or the O) was valid per block. Statistically, there was no difference between experiments except that the pre-cue benefit was bigger in Experiment 2. This may, however, be due to the fact that proportion congruence also differed between experiments.

[3] The majority of studies examining interference in Stroop tasks utilize a 4-choice design in which trials are 50 % congruent (e.g., Dishon-Berkovits & Algom, 2000). In this design, each congruent stimulus (of which there are four possible word–color pairings) is presented disproportionately more frequently than each incongruent stimulus (of which there are nine possible word–color pairings). As such, attention is attracted to the predictive word and failures of selective attention are frequent (e.g., Dishon-Berkovits & Algom, 2000; Melara & Algom, 2003), possibly the optimal conditions under which to examine the control of attention via pre-cues.

congruency pre-cues in advance of stimuli in the informative pre-cue condition. As such, any pre-cue benefit (better performance in the informative pre-cue condition compared to the non-informative pre-cue condition) is attributable to the pre-cue manipulation and not to adaptations of control that operate on the basis of experience with particular stimuli (e.g., the frequency with which one encounters incongruent and congruent stimuli; Blais et al., 2012; Bugg & Hutchison, 2013; Bugg, Jacoby, & Chanani, 2011a; for discussion of importance of ruling out these factors when drawing conclusions about top-down control, see Awh, Belopolsky, & Theeuwes, 2012).

With respect to examining the time course of preparation processes, similar to Logan and Zbrodoff (1982), we varied the cue-to-stimulus (CSI) interval and examined the effects on the magnitude of pre-cue benefits. In the current study, CSIs ranged from 500 to 2,000 ms. We chose 2,000 ms as the maximal CSI because Dyer (1974) showed that CSIs longer than 2 s were counterproductive to facilitating control when participants were given specific pre-cues that informed them of the upcoming to-be-ignored word (e.g., RED in black ink).

Experiment 1

In Experiment 1, we examined pre-cue benefits in a 4-choice color-word Stroop task under conditions of stimulus uncertainty. In the informative pre-cue condition, participants were explicitly informed that the next trial would be incongruent when a conflicting pre-cue was shown and congruent when a matching pre-cue was shown, and pre-cues were 100 % valid. In the non-informative pre-cue condition, a string of Xs that served to equate the alerting effect associated with the presentation of the cueing stimulus was presented prior to each trial. Given the use of 100 % valid pre-cues, we expected participants to switch to a word-reading strategy when a matching pre-cue was shown. Consequently, a pre-cue benefit was expected on congruent trials in the form of faster RTs in the informative relative to the non-informative pre-cue condition (Logan & Zbrodoff, 1982). Arguably, then, a pre-cue benefit on incongruent trials would be the purest indicator of a participants' ability to engage proactive control on the basis of an explicit congruency pre-cue. This is because neither the strategy of reading the word nor the strategy of switching attention to the irrelevant dimension (word) to predict the response could produce a pre-cue benefit on incongruent trials. On the basis of the DMC account's suggestion that proactive control should be evidenced with reliable pre-cues (Braver et al., 2007), we predicted a pre-cue benefit in the form of faster RTs in the informative relative to the non-informative pre-cue condition for incongruent trials.

With respect to the CSI manipulation, there is no precedence in the pre-cue literature for formulating precise predictions regarding how much time it should take to prepare an abstract proactive control setting (i.e., one that can handle stimulus uncertainty) in response to a conflicting pre-cue. Logan and Zbrodoff (1982) found generally (for congruent and incongruent trials) larger pre-cue benefits with increases in cue delay (from 100 ms to a maximal delay of 1,000 ms). However, the pre-cue benefits at the 600- and 1,000-ms delay (which approximate the 500- and 1,250-ms delays used in the present experiment) were of a very similar magnitude both for congruent and incongruent trials. This suggests that participants switched attention to the irrelevant dimension in as little as 600 ms, and there was no additional benefit of having 400 ms more preparation time. Such patterns are useful for formulating predictions regarding the effects of preparation time (i.e., CSI) on congruent trials given that participants in the current experiment were also expected to use the strategy of word reading. It may be misguided, however, to draw on these patterns to formulate predictions regarding incongruent trials because Logan and Zbrodoff's data reflect the processes supporting the strategy of switching attention to the irrelevant dimension and not the time course of preparation processes supporting proactive control (i.e., activating and maintaining the color-naming goal to bias attention to ignore whatever word appeared on incongruent trials). For the shorter CSIs, we predicted that a pre-cue benefit would be observed for congruent trials but not incongruent trials. By contrast, for the longer CSIs, we predicted that a pre-cue benefit would be found for both congruent and incongruent trials. The rationale is that participants should be able to implement a word-reading strategy (on congruent trials) with little time to prepare as well as with relatively greater time to prepare (Logan & Zbrodoff, 1982). By contrast, proactive control was expected to require more preparation time given prior accounts (e.g., Braver et al., 2007) and findings within other domains such as task switching that suggest temporal constraints on proactive control (e.g., Meiran, 1996).

Materials and methods

Participants

Nineteen undergraduates participated for course credit.[4] All participants were native English speakers with normal

[4] In this and subsequent experiments, we aimed to collect data from 24 participants. Sample sizes varied based on participant sign-ups/show-ups by end of the data collection period (e.g., semester).

or corrected vision and color vision in this and subsequent experiments. One participant's data were excluded because his/her non-informative condition data were lost due to a computer malfunction.

Stimuli and design

The experiment was programmed in E-Prime 2.0 software (Psychological Software Tools, Pittsburgh, PA, USA) and followed a 2 × 2 × 3 within-subjects design with pre-cue (non-informative vs. informative), trial type (congruent vs. incongruent), and CSI (500 vs. 1,250 vs. 2,000 ms) as factors. Pre-cues in the informative condition were either "MATCHING" (i.e., congruent) or "CONFLICTING" (i.e., incongruent) and were 100 % valid. In the non-informative condition, a string of nine Xs (XXXXXXXXX) was used that approximated the length of the informative pre-cues. Both types of pre-cues were centrally presented in black ink in 36 point, bold Arial font. The words RED, BLUE, YELLOW and GREEN and their corresponding ink colors (RGB values were 255, 0, 0; 0, 0, 255; 255, 255, 0; and 0, 128, 0, respectively) were used to create the target stimuli for the congruent and incongruent trials. The Stroop stimuli were centrally presented in 24 point Arial font. There were three CSIs (500, 1,250, and 2,000 ms), with CSI defined as the time from pre-cue onset to pre-cue offset. For each CSI, all possible congruent word/color combinations were presented equally frequently (12× each) and all possible incongruent word/color combinations were presented equally frequently (4× each) (see Table 1).

Table 1 Frequency of trial types presented in the informative and non-informative pre-cue conditions of experiments 1 and 3

CSI	Word	Color			
		Red	Blue	Yellow	Green
500	RED	*12*	4	4	4
	BLUE	4	*12*	4	4
	YELLOW	4	4	*12*	4
	GREEN	4	4	4	*12*
1,250	RED	*12*	4	4	4
	BLUE	4	*12*	4	4
	YELLOW	4	4	*12*	4
	GREEN	4	4	4	*12*
2,000	RED	*12*	4	4	4
	BLUE	4	*12*	4	4
	YELLOW	4	4	*12*	4
	GREEN	4	4	4	*12*

Within a single sub-block of 96 trials, which was 50 % congruent, only one CSI was used. The frequency of trial types was identical in the informative and non-informative pre-cue conditions. The table represents frequencies for one such condition. Values in italics represent congruent trials

Procedure

Informed consent was obtained. Participants were tested individually in a small room with the experimenter present. They were seated approximately 18 in. from the computer screen. Participants were instructed that the goal was to name the ink color in which the stimulus was printed (and not the word) as quickly as possible while maintaining a high level of accuracy. In the informative condition, participants were told that the pre-cue MATCHING meant that the color of ink would match the word for the next stimulus that is shown, and the pre-cue CONFLICTING meant that the color of ink would not match the word for the next stimulus that is shown. They were also instructed that it was very important that they try their best to utilize the information provided by the pre-cues, and were given the example of using the CONFLICTING pre-cue to ready oneself to ignore the distracting word.

Each participant completed a block that contained the informative pre-cues and a block that contained the non-informative pre-cues, and block order was counterbalanced across participants. Within each block there were three sub-blocks (one for each CSI) consisting of 96 trials (50 % congruent) and a brief break was provided between them. The order of the three CSI sub-blocks was partially counterbalanced across participants;[5] the order was held constant across the informative and non-informative conditions. As such, the informative and non-informative conditions were equated on all features except the nature of the pre-cue (see Table 1).

Prior to each block, participants completed a small set of practice trials. On practice and test trials, the Stroop stimulus was presented on a light gray ("silver": RGB 192,192,192) screen 100 ms after the offset of the pre-cue (whose duration equaled the CSI) and remained on screen until a vocal response was detected by E-prime's voice-key system (Psychological Software Tools, Pittsburgh, PA, USA). The researcher, seated next to the participant, then entered the response via keyboard. Trials on which the microphone was tripped by an irrelevant noise (e.g., a cough that triggered the offset of the stimulus from the computer screen) or on which the response was not perceptible were coded as scratch trials and not analyzed. Given the use of a blocked CSI, it was important to ensure that the inter-stimulus intervals were closely equated (i.e., to control for task pacing). Therefore, we varied the duration of the response to cue

[5] To determine whether the partial counterbalancing of sub-block (CSI) order affected the results, we entered order as a factor in the ANOVA and it did not interact with any effect, including the pre-cue × trial type interaction and the pre-cue × trial type × CSI interaction.

interval (i.e., time between the experimenter's coding of the response[6] and the next pre-cue) across sub-blocks such that the CSI and the response to cue interval (RCI) summed to 3,100 ms in each sub-block (a 100-ms blank screen occurred between the offset of the pre-cue and onset of the stimulus). For the 500-, 1,250-, and 2,000-ms CSIs (sub-blocks), the RCIs were 2,500, 1,750, and 1,000 ms, respectively. Reaction time and error rate were logged.

Results

In the present and all subsequent experiments, the alpha level was set at 0.05. In addition, partial eta-squared (η_p^2) is reported as the measure of effect size for significant effects in the ANOVA and Cohen's $d\left(2t/\sqrt{\mathrm{df}}\right)$ accompanies significant t tests. One-tailed t tests were used to perform planned comparisons to evaluate the significance of pre-cue benefits. Other than those reported, no other main effects or interactions were significant in this or subsequent experiments.

Trials faster than 200 ms or slower than 3,000 ms were trimmed, which eliminated <1 % of trials. The percent of congruent (0.0002 %) and incongruent trials (0 %) that were eliminated was very similar. Error trials were also excluded from the RT analysis.

A 2 (pre-cue: non-informative vs. informative) × 2 (trial type: congruent vs. incongruent) × 3 (CSI: 500 vs. 1,250 vs. 2,000) within-subjects ANOVA was conducted on the RT data. Mean RTs are presented in Table 2. Main effects of pre-cue, $F(1, 17) = 7.15$, MSE = 9,218, $p < 0.05$, $\eta_p^2 = 0.30$, and trial type, $F(1, 17) = 83.52$, MSE = 9,098, $p < 0.001$, $\eta_p^2 = 0.83$, were found indicating faster RTs for informative ($M = 642$, SE = 18) than non-informative pre-cues ($M = 677$, SE = 21), and congruent ($M = 600$, SE = 17) than incongruent trials ($M = 719$, SE = 22). There was not a main effect of CSI on RTs, $F < 1$. Of the two-way interactions, only the pre-cue × trial type effect was significant, $F(1, 17) = 13.90$, MSE = 1,497, $p < 0.01$, $\eta_p^2 = 0.45$, and showed that the pre-cue benefit (i.e., speeding of RTs in the informative relative to the non-informative pre-cue condition) was larger for congruent (55 ms) as compared to incongruent (16 ms) trials. Importantly, this interaction was qualified by a significant pre-cue × trial type × CSI interaction, $F(1, 17) = 4.36$, MSE = 454, $p < 0.05$, $\eta_p^2 = 0.20$ (see Table 2).

Table 2 Mean reaction times (SE) and pre-cue benefits as a function of CSI, trial type, and pre-cue condition in Experiment 1

CSI	Trial type	Pre-cue condition		Pre-cue benefit
		Informative	Non-informative	
500	Congruent	556 (21)	630 (23)	74*
	Incongruent	711 (27)	728 (25)	17
1,250	Congruent	581 (20)	631 (20)	50*
	Incongruent	720 (21)	726 (24)	6
2,000	Congruent	582 (18)	622 (19)	40*
	Incongruent	703 (19)	727 (24)	24*

Pre-cue benefit = $\mathrm{RT}_{\text{non-informative}} - \mathrm{RT}_{\text{informative}}$

CSI cue to stimulus interval

* Statistically significant benefit

To decompose the three-way interaction, we examined the pre-cue × trial type interaction separately for each CSI. For the 500-ms CSI, main effects of pre-cue, $F(1, 17) = 9.52$, MSE = 3,878, $p < 0.01$, $\eta_p^2 = 0.36$, and trial type, $F(1, 17) = 93.59$, MSE = 3,062, $p < 0.001$, $\eta_p^2 = 0.85$, were qualified by a significant interaction, $F(1, 17) = 20.25$, MSE = 746, $p < 0.001$, $\eta_p^2 = 0.54$. Planned comparisons indicated that the pre-cue benefit was significant for the congruent trials (74 ms), $t(17) = 4.09$, $p < 0.001$, $d = 1.98$, but not the incongruent trials (16 ms), $t(17) = 1.20$, $p > 0.10$. For the 1,250-ms CSI, the main effect of pre-cue was not significant, $F(1, 17) = 2.86$, MSE = 4,780, $p = 0.109$, but the main effect of trial type was, $F(1, 17) = 68.79$, MSE = 3,600, $p < 0.001$, $\eta_p^2 = 0.80$, and was qualified by a pre-cue × trial type interaction, $F(1, 17) = 12.71$, $p < 0.01$, MSE = 663, $\eta_p^2 = 0.43$. As with the 500-ms CSI, planned comparisons showed that the pre-cue benefit was significant for the congruent trials (49 ms), $t(17) = 2.57$, $p = 0.01$, $d = 1.25$, but not the incongruent trials (6 ms), $t < 1$. For the 2,000 ms CSI, there were main effects of pre-cue, $F(1, 17) = 5.32$, MSE = 3,444, $p < 0.05$, $\eta_p^2 = 0.24$, and trial type, $F(1, 17) = 64.01$, MSE = 3,553, $p < 0.001$, $\eta_p^2 = 0.79$. The pre-cue × trial type interaction was not significant, $F(1, 17) = 1.24$, MSE = 997, $p = 0.281$, indicating that the magnitude of the pre-cue benefit did not significantly differ for congruent (40 ms) and incongruent trials (24 ms). Nonetheless, given the theoretical significance, we conducted planned comparisons to determine

[6] Experimenters' response times vary trial-by-trial. Experimenters' response times (pacing) could influence the effects of interest. To examine whether this occurred in Experiment 1, we submitted the experimenters' response coding times (excluding trials faster than 100 ms or slower than 2,000 ms) to the same analyses as were conducted for participants' RTs. The only significant effect was a main effect of trial type, $F(1, 17) = 29.27$, $p < 0.001$, and it was in the opposite direction of a Stroop effect, with coding times being 26 ms slower for congruent than incongruent trials (possibly because congruent trials are responded to more quickly by the participants). Importantly, all conditions were equally likely to follow congruent and incongruent trials. Consequently, if the slight difference in pacing across the two trial types did affect performance on the following trial, it would have been equally likely to affect performance in any condition. Importantly, there was no hint of the pre-cue × trial type × CSI interaction that was found for the participants' RT data, $F < 1$.

whether the pre-cue benefits were statistically significant, and they were [$t(17) = 2.18$, $p < 0.05$, $d = 1.06$, and $t(17) = 1.90$, $p < 0.05$, $d = 0.92$, for congruent and incongruent trials, respectively].

For error rate, the 2 × 2 × 3 ANOVA revealed only a main effect of trial type, whereby fewer errors were made on congruent ($M = 0.001$, SE = 0.001) than incongruent trials ($M = 0.024$, SE = 0.007), $F(1, 17) = 11.19$, MSE = 0.002, $p < 0.01$, $\eta_p^2 = 0.40$. All other F were <2.63, $ps \geq 0.123$.

Discussion

Experiment 1 provided theoretical support for the concept of proactive control as forwarded in the DMC account (Braver et al., 2007). According to this account, proactive control is a preparation-dependent process that involves the active maintenance of the task goal (i.e., biasing of attention toward color and away from word) prior to stimulus onset (and any conflict), and is most likely to be engaged in contexts in which reliable cues are predictive of interference (i.e., yield valid expectancies). Consistent with this view, RTs were faster for incongruent trials following a pre-cue that reliably informed participants that the next trial would be conflicting than following a non-informative pre-cue. This suggests that pre-cue benefits on incongruent trials can be observed under conditions of stimulus uncertainty, contrary to a prior finding with color-word Stroop stimuli (Goldfarb & Henik, 2013, Experiment 1).

As in Logan and Zbrodoff's (1982) 2-choice task, pre-cue benefits were overall larger on congruent than incongruent trials. The effects of the CSI manipulation were informative with respect to the processes underlying the pre-cue benefits on each trial type. The interaction between pre-cue and trial type depended on the length of the CSI (preparatory interval). As expected, at the shorter CSIs, the pre-cue benefit was restricted to congruent trials and was larger than that found for incongruent trials. This pattern suggests that the strategy of word reading in response to a matching pre-cue was readily implemented within 500–1,250 ms (cf. Logan & Zbrodoff, 1982), whereas proactive control was not. At the longest CSI of 2,000 ms, however, a significant pre-cue benefit was obtained for both congruent and incongruent trials; the magnitude of these benefits did not significantly differ. Although there was no prior study that directly addressed the question of how long it might take to configure an abstract proactive control setting in response to a conflicting pre-cue, that a reliable benefit emerged only at the longest CSI for incongruent trials is consistent with the time course of preparatory control processes in other domains (e.g., Braver et al., 2007; Meiran, 1996). The pre-cue benefit for incongruent trials selectively at the longest CSI suggests that proactive control can be flexibly engaged in response to an explicit congruency pre-cue so long as sufficient time is available to prepare.

This finding also counters a possible alternative explanation that attributes the pre-cue benefit for incongruent trials to an artifact of the 4-choice 50 % congruent design used to produce stimulus uncertainty, namely that each word was paired disproportionately more frequently with its congruent color than each of the three possible incongruent colors (see Footnote 3). In designs such as this, attention tends to be attracted to the predictive but nominally irrelevant word (e.g., Melara & Algom, 2003). Given this tendency, one might argue that it is unsurprising that RTs were slower on incongruent trials when pre-cues did not inform participants that the upcoming word would conflict with the color (i.e., the non-informative pre-cue condition). However, attending to the word was equally beneficial for all CSIs (because all were 50 % congruent) in the non-informative pre-cue condition not just the longest CSI. Therefore, slowing (and consequently, according to this explanation, pre-cue benefits) should have been apparent for all CSIs not just the longest.

Experiment 2

The current experiment aimed to examine the role of preparation time in a 4-choice, 50 % congruent design that biased adoption of a (reactive) attention-switching strategy rather than proactive control. The design of Experiment 2 was identical to Experiment 1 with one small but theoretically important difference. Instead of pairing each word with all possible colors (one congruent, three incongruent), each word was paired with its corresponding congruent color and one unique incongruent color (see Table 3; cf. Logan et al., 1984). Consequently, participants could adopt the strategy of switching attention to the irrelevant word and using it to predict the single associated response when presented with a conflicting pre-cue, similar to the participants in Logan and Zbrodoff's (1982) 2-choice task (for view that learning and use of the word–color correlations may be implicit, see Musen & Squire, 1993; Schmidt & Besner, 2008). Given this difference, we predicted that pre-cue benefits might be observed for congruent and incongruent trials not only at the longest CSI (as in Experiment 1) but also at the shorter CSIs, including 500 ms (see Logan & Zbrodoff's, 1982, Fig. 1 for what appears to be a pre-cue benefit on incongruent trials at the 400-ms cue delay). Such a pattern would be consistent with use of an attention-switching strategy that primarily operates post-stimulus onset (i.e., to know which response to reactively predict) rather than being preparation-dependent like proactive control.

Table 3 Frequency of trial types presented in the informative and non-informative pre-cue conditions of Experiment 2

CSI	Word	Color			
		Red	Blue	Yellow	Green
500	RED	*12*	12	0	0
	BLUE	0	*12*	12	0
	YELLOW	0	0	*12*	12
	GREEN	12	0	0	*12*
1,250	RED	*12*	12	0	0
	BLUE	0	*12*	12	0
	YELLOW	0	0	*12*	12
	GREEN	12	0	0	*12*
2,000	RED	*12*	12	0	0
	BLUE	0	*12*	12	0
	YELLOW	0	0	*12*	12
	GREEN	12	0	0	*12*

Within a single sub-block of 96 trials, which was 50 % congruent, only one CSI was used. The frequency of trial types was identical in the informative and non-informative pre-cue conditions. The table represents frequencies for one such condition. Values in italics represent congruent trials

Materials and methods

Participants

Twenty-four participants (19 undergraduates) aged 18–24 years took part in the study for course credit or monetary compensation.

Stimuli and design

The stimuli and design were the same as Experiment 1, with a few key exceptions. Fifty percent of trials in each sub-block were congruent, as in the preceding experiments. However, we used a subset of possible word/color combinations on incongruent trials such that each word was associated with a single and unique incongruent color. Each word was then presented equally frequently as a congruent trial (48× each) and an incongruent trial (48× each) for each CSI (see Table 3).

Procedure

The procedure was identical to Experiment 1.[7]

[7] The analysis of the experimenters' response coding times revealed a similar pattern as in Experiment 1. The main effect of trial type indicated 9 ms faster coding for incongruent than congruent trials. There was also a main effect of CSI in Experiment 2 due to the experimenter taking ~30 ms longer to code responses in the short than the two longer CSI conditions, $F(2, 46) = 3.27$, $p = 0.047$. Moreover, the pre-cue × trial type interaction found for participants' RT data was not observed in the experimenters' coding time data, $F < 1$.

Results

The trimming procedures were identical to the previous experiment and eliminated <1 % of trials. An equivalent percent of congruent (0.002 %) and incongruent trials (0.002 %) was eliminated. A 2 (pre-cue: non-informative vs. informative) × 2 (trial type: congruent vs. incongruent) × 3 (CSI: 500 vs. 1,250 vs. 2,000) within-subjects ANOVA was conducted on the RT data. Mean RTs are presented in Table 4. Main effects of pre-cue condition, $F(1, 23) = 59.34$, MSE = 7,866, $p < 0.001$, $\eta_p^2 = .721$, trial type, $F(1, 23) = 189.17$, MSE = 3,229, $p < 0.001$, $\eta_p^2 = 0.892$, and CSI, $F(2, 46) = 11.63$, MSE = 2,174, $p < 0.001$, $\eta_p^2 = 0.336$, were found indicating faster RTs for informative ($M = 606$, SE = 19) than non-informative pre-cues ($M = 687$, SE = 21), slower RTs on incongruent ($M = 692$, SE = 20) than congruent ($M = 600$, SE = 19) trials, and slower responses for the shorter CSI. The pre-cue × trial type interaction was significant, $F(1, 23) = 39.87$, MSE = 1,118, $p < 0.001$, $\eta_p^2 = 0.634$. Planned comparisons (one-tailed t tests) indicated that a significant pre-cue benefit was found for congruent ($M = 105$ ms), $t(23) = 8.06$, $p < 0.001$, $d = 3.36$, and incongruent trials ($M = 56$ ms), $t(23) = 6.27$, $p < 0.001$, $d = 2.61$, with the benefit being larger for congruent trials as in the preceding experiment. No other two-way interaction was significant (Fs < 1), nor was the three-way pre-cue × trial type × CSI interaction, $F(2, 46) = 1.08$, MSE = 443, $p = 0.348$. As shown in Table 4, the pre-cue benefits for congruent trials were sizable for each CSI as were the pre-cue benefits for incongruent trials. For completeness, given their theoretical significance, planned comparisons were also conducted to determine if the pre-cue benefits were significant for congruent and incongruent trials for each CSI, and they were (for congruent: ts ≤ 5.96, ps < 0.001, ds > 2.48; for incongruent: ts ≤ 3.18, ps < 0.01, ds > 1.32).

Table 4 Mean reaction times (SE) and pre-cue benefits as a function of CSI, trial type, and pre-cue condition in Experiment 2

CSI	Trial type	Pre-cue condition		Pre-cue benefit
		Informative	Non-informative	
500	Congruent	527 (18)	634 (22)	107*
	Incongruent	642 (16)	709 (22)	67*
1,250	Congruent	556 (22)	656 (23)	100*
	Incongruent	673 (23)	716 (21)	43*
2,000	Congruent	559 (20)	668 (21)	109*
	Incongruent	678 (22)	734 (23)	56*

CSI cue to stimulus interval

Pre-cue benefit = $RT_{non\text{-}informative} - RT_{informative}$

* Statistically significant benefit

For error rate, an identical ANOVA was performed. There were no significant effects with the exception of a main effect of trial type due to incongruent trials incurring 1.5 % more errors than congruent trials, $F(1, 23) = 27.91$, $MSE = 0.001$, $p < 0.001$, $\eta_p^2 = 0.548$.

Discussion

Comparing the present findings to those of Experiment 1, which used the traditional iteration of the 4-choice, 50 % congruent design that produces stimulus uncertainty, the major similarity was that the pre-cue benefit was again larger for congruent than incongruent trials (see also Logan & Zbrodoff, 1982). However, there were also two theoretically important differences. First, large and reliable pre-cue benefits were observed for congruent and incongruent trials for all CSIs in the present experiment whereas the pre-cue benefit for incongruent trials was significant only at the longest CSI in Experiment 1. These patterns are consistent with the view that participants used a strategy that was not dependent on having sufficient preparation time in response to both matching and conflicting pre-cues in the current experiment. On congruent trials, participants likely read the words as in the preceding experiment given the use of 100 % valid pre-cues. On incongruent trials, participants were able to switch attention to the word to predict (post-stimulus onset) the single associated incongruent response color and accordingly, as in Logan and Zbrodoff's (1982) study, pre-cue benefits also emerged at the two shorter CSIs (500 and 1,250 ms). The overall larger pre-cue benefit for congruent than incongruent trials suggests that reading speeded RTs more than the attention-switching strategy used on incongruent trials.

Second, the magnitude of the pre-cue benefit on incongruent as well as congruent trials was on average larger in the present experiment (16 vs. 56 ms benefit for incongruent and 55 vs. 105 ms benefit for congruent in Experiments 1 and 2, respectively). This pattern may relate to the common use of primarily reactive strategies across trial types in the present experiment; consistently attending to the irrelevant dimension in the informative pre-cue condition (though using that dimension differently for congruent than incongruent trials) may have minimized costs of switching from a reactive strategy to proactive control and vice versa.

Experiment 3

In Experiment 3, we returned to the 4-choice, 50 % congruent design used in Experiment 1 and examined whether cue validity alters the effectiveness of pre-cues. As Posner et al. (1980) noted, it is not only the benefits but also the costs of cueing that provide insights into the knowledge participants have about an expected event. Motivated by Posner et al.'s (1980) approach to examining the effects of cue validity on stimulus detection, we reduced the validity of the pre-cues in the present experiment to 75 %. Hence, on 25 % of the trials, the explicit pre-cues were misleading. That is, one's expectations (e.g., matching pre-cue) conflicted with subsequent experience (e.g., incongruent trial).

According to the DMC account, proactive control is mostly likely to be operative when cues reliably forecast interference (Braver et al., 2007). In the preceding experiments, the pre-cues were 100 % valid and hence, highly reliable. It was uncertain whether 75 % valid pre-cues would be utilized to the same degree and therefore it was questionable whether pre-cue benefits would be found when contrasting the informative and non-informative pre-cue conditions in the current experiment. Consider, for example, the conflicting pre-cue. If engagement of proactive control (e.g., preparing attention to avoid processing of the word) in response to this type of pre-cue is effortful, the fact that such effort would not pay off on a quarter of trials could be sufficient to deter use of the pre-cue even when enough time was provided to prepare (i.e., 2,000 ms CSI). Similarly, participants might not engage in a word-reading strategy in response to the matching pre-cue given the steep cost to performance (i.e., production of errors) on the quarter of trials on which an incongruent stimulus appeared. If so, then the pre-cue benefits in the present experiment might be different from those of Experiment 1.

Materials and methods

Participants

Twenty-four undergraduates participated for course credit.

Stimuli and design

The stimuli and design were the same as Experiment 1 (see Table 1 for frequency of trial types), with one key exception. In this experiment, the pre-cues in the informative pre-cue condition were 75 % valid. This meant that, for a given cell in Table 1, such as that reflecting that the word RED was shown in red ink 12 times at the 500 ms CSI, 75 % (9) of those trials were valid (preceded by a MATCHING cue) and 25 % (3) were invalid (preceded by a CONFLICTING cue). The resultant design was a 3 (pre-cue) × 2 (trial type) × 3 (CSI) within-subjects design with the three pre-cue levels being non-informative, informative-valid, and informative-invalid.

Table 5 Mean reaction times (SE) and pre-cue benefits as a function of CSI, trial type, and pre-cue condition in Experiment 3

CSI	Trial type	Pre-cue condition			Pre-cue benefit
		Informative-valid	Informative-invalid	Non-informative	
500	Congruent	604	620	605	1
	Incongruent	730	728	711	−19
1,250	Congruent	617	619	629	12
	Incongruent	739	751	722	−17
2,000	Congruent	618	625	630	12
	Incongruent	729	757	722	−7

Pre-cue benefit = $RT_{non\text{-}informative} - RT_{informative\text{-}valid}$

CSI cue to stimulus interval

* Statistically significant benefit

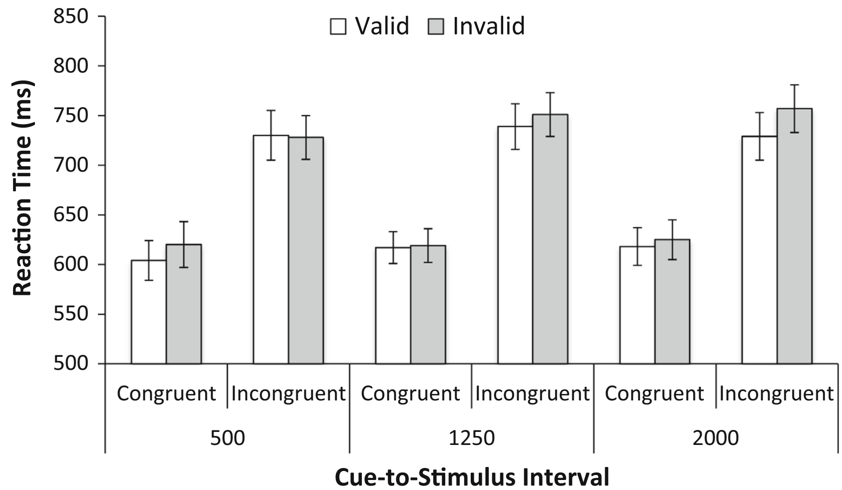

Fig. 1 Mean reaction time (ms) for valid as compared to invalid pre-cues in the informative pre-cue condition (i.e., the cue validity effect) of Experiment 3 as a function of cue-to-stimulus interval and trial type. *Error bars* represent standard error of the mean

Procedure

Experiment 3 followed the same procedure as Experiment 1;[8] however, participants were informed that the pre-cues were mostly but not 100 % valid. Specifically, they were instructed that a MATCHING pre-cue meant that the color of the ink would very likely match the word for the next stimulus and a CONFLICTING pre-cue meant it would very likely not match the word for the next stimulus.

Results

The trimming procedures were identical to the previous experiments and eliminated <1 % of trials. Again, the percent of congruent (0.0002 %) and incongruent trials (0.0005 %) that were eliminated was very similar. We conducted two sets of analyses to examine the primary questions. The first mirrored the primary analysis in the preceding experiments and examined the effects of having versus not having the pre-cues (i.e., possible pre-cue benefits) by comparing performances across the informative and non-informative pre-cue conditions. The second analysis was aimed at examining the cue validity effect (i.e., possible costs of invalidity) within the informative pre-cue condition.

Pre-cue effect

To examine possible pre-cue benefits, we performed a 2 (pre-cue: non-informative vs. informative-valid) × 2 (trial type: congruent vs. incongruent) × 3 (CSI: 500 vs. 1,250 vs. 2,000) within-subjects ANOVA on the RT data. Mean RTs are presented in Table 5. For comparability to the preceding experiments, this analysis excluded the invalid trials from the informative pre-cue condition. There was a main effect of trial type, $F(1, 23) = 101.28$, MSE = 8,360, $p < 0.001$, $\eta_p^2 = 0.82$, and it was qualified by a pre-cue × trial type interaction, $F(2, 46) = 10.70$, MSE = 832, $p < 0.01$, $\eta_p^2 = 0.32$. Planned comparisons (one-tailed t tests) indicated that on congruent trials there was a small and non-significant pre-cue benefit of 8 ms, $t(23) = 1.13$, $p = 0.269$, whereas on incongruent trials, participants were 14 ms slower in the informative pre-cue condition than the non-informative pre-cue condition and this difference was also non-significant, $t(23) = 1.16$, $p = 0.743$. While the two-way CSI × trial type interaction approached significance, $F(2, 46) = 2.79$, MSE = 503,

[8] In Experiment 3, there were no significant effects in the analysis of experimenters' response coding times.

$p = 0.072$, the three-way interaction did not, $F < 1$ (see Table 5).

For error rate, the ANOVA revealed only a main effect of trial type, $F(1, 23) = 7.15$, MSE < 0.001, $p < 0.05$, $\eta_p^2 = 0.24$. There were slightly more errors on incongruent trials ($M = 0.007$, SE $= 0.001$) than congruent trials ($M = 0.003$, SE $= 0.001$).

Cue validity effect

A 2 (validity: informative-valid vs. informative-invalid) × 2 (trial type: congruent vs. incongruent) × 3 (CSI: 500 vs. 1,250 vs. 2,000) within-subjects ANOVA was conducted on the RT data from the informative pre-cue condition (see Table 5 for means). Main effects of trial type, $F(1, 23) = 109.29$, MSE $= 9{,}735$, $p < 0.001$, $\eta_p^2 = 0.83$, and validity, $F(1, 23) = 5.71$, MSE $= 1{,}404$, $p < 0.05$, $\eta_p^2 = 0.20$, were qualified by a trial type × validity × CSI interaction, $F(2, 46) = 3.85$, MSE $= 678$, $p < 0.05$, $\eta_p^2 = 0.14$. As shown in Fig. 1, this interaction reflected that for incongruent trials, $F(2, 46) = 4.24$, MSE $= 671$, $p < 0.05$, $\eta_p^2 = 0.16$, but not congruent trials, $F < 1$, the effects of validity differed across CSIs. For incongruent trials, planned comparisons (one-tailed *t* tests) indicated that a significant, 28 ms cost of invalidity was found at the longest (2,000 ms) CSI, $t(23) = 2.55$, $p < 0.001$, $d = 1.06$. Neither the 12 ms cost at the 1,250 ms CSI, $t(23) = 1.36$, $p = 0.094$, nor the 3 ms cost at the 500 ms CSI, $t < 1$, was significant. For congruent trials, the costs were 17, 2, and 7 ms with increasing CSI, and non-significant, $ts < 1.32$, $ps > 0.202$.

For error rate, the 2 × 2 × 3 within-subjects ANOVA revealed only a main effect of trial type, $F(1, 23) = 6.15$, MSE $= 0.001$, $p < 0.05$, $\eta_p^2 = 0.21$, with errors being 1 % more frequent on incongruent ($M = 0.012$, SE $= 0.004$) than congruent trials ($M = 0.002$, SE $= 0.001$) (All other $Fs < 2.19$, $ps \geq 0.087$).

Discussion

The present experiment examined the effects of a cue validity manipulation on possible costs and benefits of expectancies regarding the likelihood of interference. Toward this end, we used pre-cues that were 75 % valid rather than 100 % valid. There were two major findings. First, there was not a significant pre-cue benefit on either congruent or incongruent trials (i.e., in neither case were the RTs faster on valid trials in the informative pre-cue condition compared to the non-informative pre-cue condition). This is consistent with our speculation that participants might not apply a word-reading strategy in response to matching pre-cues and might not fully engage proactive control in response to conflicting pre-cues because of the potential costs on invalidly cued trials. Because the only difference between the current experiment and Experiment 1 (other than the participants) was the use of 75 % as opposed to 100 % valid pre-cues, it can be concluded that participants were sensitive to cue validity. Participants may be unwilling to switch attention to a word-reading strategy or prepare proactively in response to cues indicating a high probability of conflict when probabilistic cues are used, at least under non-incentivized conditions. Indeed, using a paradigm in which participants were informed that an upcoming list would be mostly (80 %) conflicting trials, Bugg et al. (in press) found that participants did not utilize the pre-cues. That is, they showed no less interference when cued than when they were not cued. However, when participants were provided with incentives for performing well, they did utilize the mostly conflicting pre-cues to minimize interference on the first trial following the pre-cue. Consistent with the theory of the expected value of control (Shenhav, Botvinick, & Cohen, 2013), these findings suggest that control may be allocated in response to probabilistic cues when the expected reward “justifies” the expected effort and amount of control.

Second, with respect to the cue validity effect, there was a cost associated with invalid expectancies selectively for incongruent trials at the longest CSI. Put simply, it was more difficult for participants to name the color of the stimulus when they encountered an unexpectedly interfering word (matching pre-cue—incongruent trial) than when they encountered an expectedly interfering word (conflicting pre-cue—incongruent trial) at the 2,000-ms CSI. The absence of a pre-cue benefit for incongruent trials at the longest CSI may seem at odds with the presence of a cue validity effect for incongruent trials at the longest CSI. The pre-cue benefit, however, likely reflects a somewhat different process than the cue validity effect. The former is derived from a contrast between the informative and non-informative pre-cue conditions whereas the latter is derived by contrasting valid and invalid trials within the informative pre-cue condition. The absence of a pre-cue benefit for incongruent trials at the 2,000-ms CSI suggests that the degree of proactive control engagement in response to the conflicting pre-cue in the informative condition (with 75 % valid pre-cues) was insufficient to produce a benefit relative to the degree of control (e.g., based on adaptations due to stimulus frequencies) in the non-informative condition. Within the informative pre-cue condition, however, validity mattered. The cue validity effect for incongruent trials at the 2,000-ms CSI suggests that there was greater engagement of proactive control in response to conflicting than to matching pre-cues and/or there was a cost to actively relaxing control when the matching but not the conflicting pre-cue was shown (cf. Gratton et al., 1992).

Experiment 4

To take stock, only Experiment 1 provided evidence of a preparation-dependent, proactive biasing of attention in response to conflicting pre-cues under conditions of stimulus uncertainty. That pattern was not observed in Experiments 2 or 3. Although we did not expect to find evidence of proactive control in Experiment 2 and there are theoretical reasons why the pattern was not apparent in Experiment 3 (e.g., probabilistic rather than 100 % valid cues and no incentive), one might still view the latter as a failure to replicate Experiment 1. The purpose of Experiment 4 therefore was to systematically replicate the key pattern from Experiment 1, namely the preparation-dependent use of 100 % valid conflicting pre-cues. A similar design was employed but with four CSIs ranging from 500 to 2,000 ms. In addition, rather than using a single CSI per sub-block as in Experiment 1, the CSIs were randomly intermixed in each sub-block. The predictions were the same as in Experiment 1.

Materials and methods

Participants

Twenty-four undergraduates participated for course credit.

Stimuli and design

The materials and design were identical to Experiment 1 with one important exception. There were four CSIs rather than three resulting in a 2 (pre-cue: non-informative vs. informative) × 2 (trial type: congruent vs. incongruent) × 4 (CSI: 500 vs. 1,000 vs. 1,500 vs. 2,000) within-subjects design. All (four) congruent trials (e.g., RED in red, BLUE in blue, etc.) were presented equally frequently (9× each) and all (12) incongruent trials (e.g., RED in blue, BLUE in yellow, etc.) were presented equally frequently (3× each) for each CSI (see Table 6).

Procedure

As in Experiment 1,[9] each participant completed a block that contained the informative pre-cues and a block that contained the non-informative pre-cues. These blocks were counterbalanced such that an equal number of participants completed the conditions in each order. Within each block, there were three sub-blocks, and a brief break was provided between them. Each sub-block consisted of 96 stimuli with 48 presentations of both congruent and incongruent stimuli, which were randomly intermixed. Unlike in the preceding experiments, CSIs were randomly intermixed within a sub-block, with an equal number of trials for each CSI. Across sub-blocks, there were 36 congruent and 36 incongruent trials representing each CSI. The informative and non-informative pre-cue conditions were equated on all features except the nature of the pre-cue (see Table 6).

[9] In Experiment 4, we confirmed that pacing of experimenters' response coding did not affect the effects of interest.

Table 6 Frequency of trial types presented in the informative and non-informative pre-cue conditions of Experiment 4

CSI	Word	Color			
		Red	Blue	Yellow	Green
500	RED	*9*	3	3	3
	BLUE	3	*9*	3	3
	YELLOW	3	3	*9*	3
	GREEN	3	3	3	*9*
1,000	RED	*9*	3	3	3
	BLUE	3	*9*	3	3
	YELLOW	3	3	*9*	3
	GREEN	3	3	3	*9*
1,500	RED	*9*	3	3	3
	BLUE	3	*9*	3	3
	YELLOW	3	3	*9*	3
	GREEN	3	3	3	*9*
2,000	RED	*9*	3	3	3
	BLUE	3	*9*	3	3
	YELLOW	3	3	*9*	3
	GREEN	3	3	3	*9*

Within a single sub-block of 96 trials, one-third of the total number of trials within a cell was presented. As such, sub-blocks were 50 % congruent. The frequency of trial types was identical in the informative and non-informative pre-cue conditions. The table represents frequencies for one such condition. Values in italics represent congruent trials

Results

Trimming was identical to the previous experiments and eliminated <1 % of trials. The percent of congruent (0 %) and incongruent trials (0.001 %) that were eliminated was very similar. A 2 (pre-cue: non-informative vs. informative) × 2 (trial type: congruent vs. incongruent) × 4 (CSI: 500 vs. 1,000 vs. 1,500 vs. 2,000) within-subjects ANOVA was conducted on the RT data. Mean RTs are presented in Table 7. RTs were faster in the informative condition ($M = 708$, SE = 23) than the non-informative condition ($M = 763$, SE = 22), $F(1, 23) = 12.65$, MSE = 22,998, $p < 0.01$, $\eta_p^2 = 0.36$, and on congruent trials ($M = 658$, SE = 19) than incongruent trials ($M = 813$, SE = 24), $F(1, 23) = 165.53$, MSE = 13,820, $p < 0.001$, $\eta_p^2 = 0.88$. A main effect of CSI was also found, $F(3, 69) = 17.23$, MSE = 2,532, $p < 0.001$, $\eta_p^2 = 0.43$, and post hoc

Table 7 Mean reaction times (SE) and pre-cue benefits as a function of CSI, trial type, and pre-cue condition in Experiment 4

CSI	Trial type	Pre-cue condition		Pre-cue benefit
		Informative	Non-informative	
500	Congruent	657 (27)	715 (22)	58*
	Incongruent	836 (32)	860 (30)	24
1,000	Congruent	605 (23)	686 (18)	80*
	Incongruent	790 (27)	818 (25)	27
1,500	Congruent	602 (19)	687 (22)	84*
	Incongruent	783 (27)	814 (24)	31
2,000	Congruent	611 (19)	704 (19)	93*
	Incongruent	779 (23)	822 (24)	43*

Pre-cue benefit = $RT_{non\text{-}informative} - RT_{informative}$

CSI cue to stimulus interval

* Statistically significant benefit

comparisons indicated that RTs were significantly slower at the 500 ms CSI ($M = 767$, SE = 24) relative to all other CSIs ($M = 725$), $ps \leq 0.001$, which did not significantly differ from each other ($ps \geq 0.165$). The main effects were qualified by two, two-way interactions. Most critically, there was a pre-cue × trial type interaction. The pre-cue benefit was larger for congruent (79 ms) as compared to incongruent (31 ms) trials, $F(1, 23) = 21.47$, MSE = 2,527, $p < 0.001$, $\eta_p^2 = 0.48$. Planned comparisons (one-tailed *t* tests) contrasting mean RTs in the informative pre-cue condition to the non-informative pre-cue condition indicated that the pre-cue benefit was significant for congruent trials, $t(23) = 5.08$, $p < 0.001$, $d = 2.12$, and incongruent trials, $t(23) = 1.83$, $p < 0.05$, $d = 0.76$. There was also a pre-cue × CSI interaction showing that the RT advantage associated with the informative pre-cue increased with increases in CSI, $F(3, 69) = 3.41$, MSE = 887, $p < 0.05$, $\eta_p^2 = 0.13$. The increase followed a linear pattern from a 41-ms benefit in the 500-ms condition to 54-, 57-, and 68-ms benefits at the three progressively longer CSIs. This pattern did not significantly differ for congruent and incongruent trials as indicated by the non-significant pre-cue × trial type × -CSI interaction, $F < 1$. Although this was the case, it was of theoretical interest to determine whether pre-cue benefits for congruent and incongruent trials were significant at particular CSIs. For congruent trials, the pre-cue benefits were significant at each CSI (58, 80, 84, and 93 ms, respectively, with increasing CSI), $ts > 2.98$, $ps < 0.01$, $ds > 1.24$. For incongruent trials, the pre-cue benefits at the 500-, 1,000-, and 1,250-ms CSI (24, 27, and 31 ms, respectively) were not significant, $ts \leq 1.64$, $ps \geq 0.057$. However, the pre-cue benefit at the 2,000 ms CSI (43 ms) was significant, $t(23) = 3.08$, $p < 0.01$, $d = 1.28$.

For error rate, the 2 × 2 × 4 ANOVA revealed only a main effect of trial type, whereby fewer errors were made on congruent ($M = 0.003$, SE = 0.001) than incongruent trials ($M = 0.029$, SE = 0.004), $F(1, 23) = 47.80$, MSE = 0.001, $p < 0.001$, $\eta_p^2 = 0.68$. All other *F* were <1.

Discussion

The findings of Experiment 4 converged with those of Experiment 1 in providing evidence that, under select conditions, 100 % valid pre-cues that signal the congruency of the upcoming trial facilitate proactive control. Pre-cue benefits on incongruent trials increased in magnitude as CSI increased with the only significant benefit emerging when participants had 2,000 ms to prepare following the pre-cue. A pre-cue benefit was also found for the congruent trials (those preceded by the matching cue) and was larger than the benefit on incongruent trials, consistent with Experiment 1. This is unsurprising considering that a word-reading strategy was likely used on congruent trials given the 100 % valid nature of the pre-cues.

What was somewhat surprising was the absence of a pre-cue × trial type × CSI interaction. At the shortest CSI in the present experiment, the pre-cue benefit was smaller (relative to the longer CSIs) not only for incongruent (as anticipated and observed in Experiment 1) but also congruent trials. This may be due to our random mixing of the CSIs within sub-blocks. When CSIs are mixed, participants do not know how much time will elapse (after the onset of the pre-cue) prior to stimulus onset. Because 75 % of precued trials had CSIs of 1,000 ms or longer, it was reasonable for participants to expect to have at least a second before the stimulus appeared such that having less time (i.e., 500-ms CSI) was rather unexpected. For incongruent trials, it is unlikely that the "surprisingness" of the short preparation interval precluded a pre-cue benefit that would otherwise have been present. This is because 500 ms was thought to be insufficient time to prepare proactive control. For congruent trials, however, 500 ms was thought to be sufficient time to switch to reading the word (Logan & Zbrodoff, 1982; see also Experiments 1 and 2). For these trials, then, the unexpected brevity of the preparation interval (500 ms) may have precluded finding what would otherwise have been a larger pre-cue benefit (and consequently, may have resulted in the absence of the three-way interaction). Supporting this interpretation, Altmann and Gray (2008) found that in a within-block mixed CSI task-switching experiment, participants prepared less than optimally for the shortest CSIs, reaching the maximal state of readiness at too late of a time point (due to the presence of longer CSIs).

All and all, the findings of Experiment 4 replicated those of Experiment 1. Most importantly, they showed that when

100 % valid pre-cues are used, there is a pre-cue benefit on incongruent trials selectively at the 2,000-ms CSI, consistent with a preparation-dependent, proactive control mechanism. That the magnitude of the pre-cue benefits on incongruent trials was overall larger in the present experiment, and the benefit at the 1,500-ms delay approached significance is theoretically interesting. Future studies are needed to further characterize the time course of preparatory processes in pre-cuing paradigms and better understand factors that influence the magnitude of pre-cue benefits on incongruent trials (e.g., perhaps pre-cues are more likely to be used in less predictable contexts).

General discussion

The current study demonstrated variable effects of explicit trial-by-trial congruency pre-cues on the cognitive control of interference. One theoretically important finding was that pre-cue benefits on incongruent trials under conditions of stimulus uncertainty were present only at the longest CSI (Experiments 1 and 4) whereas such benefits were apparent for all CSIs including the shortest (500 ms) when the strategy of switching attention to the irrelevant dimension was viable (Experiment 2; cf. Logan & Zbrodoff, 1982, findings at the 400-ms cue delay). This suggests that the engagement of proactive control in response to a conflicting pre-cue is a preparation-dependent process, consistent with the DMC account (Braver et al., 2007). By contrast, the strategy of switching attention to the irrelevant dimension appears to be primarily reactive in nature with the underlying processes (e.g., prediction of color based on word) occurring post-stimulus onset (cf. Logan & Zbrodoff, 1982). Indeed, this strategy mimicked the time course of pre-cue benefits on congruent trials where participants were very likely reading the words upon stimulus onset (Experiments 1, 2, and 4). Collectively, these patterns suggest that trial-by-trial congruency pre-cues, though available in advance of stimulus onset, do not always stimulate use of proactive control *a la* the DMC account (i.e., a preparation dependent mechanism).

A second theoretically important finding was that pre-cue benefits varied as a function of pre-cue validity. Significant pre-cue benefits were observed for congruent and incongruent trials under conditions of stimulus uncertainty when pre-cues were 100 % valid (Experiments 1 and 4) but were not observed for either trial type when pre-cues were 75 % valid (Experiment 3). The DMC account posits that cues must be highly reliable in order for proactive control to be implemented (Braver et al., 2007). In the present experiments, it appears that participants were reluctant to engage the effort necessary to prepare proactive control when it was uncertain whether that effort would be useful (i.e., when cues were not 100 % valid).

The lack of pre-cue benefits with 75 % valid pre-cues is intriguing in light of prior findings showing modulations of control based on probabilistic interference. One clear example is the list-wide proportion congruence effect. The likelihood that a list (or item within a list; Bugg et al., 2008) is interfering is often 75 % valid, and lists that are less valid (e.g., 60 %) still yield marginal proportion congruency effects (e.g., Blais et al., 2012). One possibility, as some have suggested (Blais et al., 2012), is that these effects reflect implicit adaptations rather than explicit or intentional strategy use; if so, then choice to engage effort may be less dependent on "cue" validity in the list-wide proportion congruence paradigm than in the explicit, trial-by-trial pre-cueing paradigm. Consistent with this view, Bugg et al. (in press) found that participants were unlikely to intentionally utilize probabilistic pre-cues signaling the next list would be mostly (80 %) conflicting unless they were motivated to engage the effort via incentives (in which case a benefit was found on the first trial following the cue). Another possibility relates to the dynamic nature of the present pre-cueing paradigm—a pre-cue may be applicable for just a single trial before a different cue is shown and a new setting must be adopted (e.g., read the word vs. proactively bias attention toward goal-relevant information). In the list-wide proportion congruence paradigm, a uniform setting (e.g., proactively bias attention toward goal-relevant information if most of trials are incongruent) can be applied across trials, possibly making adoption of such a setting more appealing under probabilistic conditions. Consistent with this view, Bugg et al. (in press) found that participants did use mostly (80 %) matching pre-cues when the cues applied to a list of trials unlike participants in Experiment 3 who did not use the likely matching pre-cue that applied to a single upcoming trial. Contrary to this view, however, Bugg et al. found no evidence for the intentional heightening of proactive control in a sustained fashion across the course of a list when participants were cued the next list would be mostly conflicting. The opportunity to further evaluate differences in the mechanisms that underlie control adjustments based on explicit vs. implicit expectancies at the trial and list level represents an exciting direction for future research.

Comparison to prior findings

As noted at the outset, there are very few studies that have examined the effects of pre-cueing congruency on cognitive control in the Stroop task under conditions that are important for drawing conclusions about proactive control (e.g., stimulus uncertainty). The findings of Experiments 1 and 4 converged with those of Goldfarb and Henik's (2013) second experiment (but see their first experiment) in providing evidence for proactive control of Stroop interference.

Although we did not use an identical design to Goldfarb and Henik (e.g., they intermixed informative and non-informative pre-cues in a block whereas we manipulated pre-cue type between blocks; see also Logan & Zbrodoff, 1982), both studies utilized what Wühr and Kunde (2008) referred to as "reliable cues", save for the present Experiment 3. This contrasts with the approach of using "unreliable cues" in which a given cue (e.g., the letter A or a plus sign) is 80 % predictive of congruent trials, another is 80 % predictive of incongruent trials, and a third is neutral (50 % predictive of either trial type) (see Gratton et al., 1992; Ghinescu, Schachtman, Stadler, Fabiani, & Gratton, 2010; for implementation in a 2-choice flanker task). Using this approach in a color-word Stroop task, Lamers and Roelofs (2011) found a large reduction in interference for cues predicting an 80 % likelihood of an incongruent trial compared to those predicting an 80 % likelihood of a congruent trial; the reduction in interference for a cue predicting an 80 % likelihood of an incongruent trial compared to a cue predicting a 50 % likelihood was much smaller but also significant (but see Gratton et al., 1992).

As Wühr and Kunde (2008) noted, such patterns can be difficult to interpret; for example, more practice with incongruent stimuli following the 80 % incongruent cue may explain the decreased interference. This may explain why we found a different pattern of benefits with use of 75 % valid pre-cues in Experiment 3. Alternatively, the differing findings may be due to Lamers and Roelofs' use of a subset of possible incongruent stimuli (i.e., not meeting the conditions of stimulus uncertainty). Each word was associated with a single incongruent color in their 3-choice task. Participants may have learned to (reactively) use the word to predict the associated response (color), as in the present Experiment 2, producing a benefit in the 80 % incongruent cue condition. Future studies should directly investigate potential differences between the various designs (i.e., reliable cues in mixed blocks vs. between blocks designs; unreliable cues) used to examine pre-cue benefits and the implications for drawing conclusions regarding proactive control.

Alternative explanations

The DMC account described proactive control as the active maintenance of task goals in a preparatory fashion to bias attention toward goal-relevant information prior to stimulus onset (Braver et al., 2007). The findings of Experiments 1 and 4 suggest that proactive control can be evidenced albeit under highly select conditions of stimulus uncertainty, namely when participants have sufficient time to prepare and cues are 100 % valid. These findings emerged in blocks in which 50 % of trials were congruent, consistent with Goldfarb and Henik's (2013) suggestion that pre-cues may be most effective when block-wide congruency does not (already) stimulate maximal levels of proactive control. While our findings and those of Goldfarb and Henik provide limited support for the DMC account (Braver et al., 2007), the precise processes that underlie proactive control merit further investigation. For instance, proactive control may be an emergent property that arises as a consequence of maintaining the task goal in an active state (i.e., in working memory; Courtney, 2004). Alternatively, proactive control may entail a separate set of processes that are implemented (centrally) by the brain. For example, pre-cue benefits on incongruent trials may reflect gating, the differential weighting of the irrelevant dimension in an anticipatory fashion in response to pre-cues (i.e., Wühr & Kunde, 2008) or the operation of a word-reading filter (Jacoby, McElree, & Trainham, 1999) reflecting the inhibition of word-processing regions of the brain. Yet another account is that proactive control in the present and Goldfarb and Henik's (2013) trial-by-trial pre-cueing paradigm may be "achieved" by peripheral strategies such as vision blurring or averting gaze to a peripheral location. Though such strategies seem to be voluntary and, like proactive control, achieve the goal of following the task instructions to name the color and ignore the word, they do not appear to capture the essence of the central proactive control mechanism described in the DMC account (Braver et al., 2007; see also neuroimaging findings of DePisapia & Braver, 2006).

A number of findings suggest that peripheral strategies are unlikely to underlie the pre-cue benefits. First, pre-cue benefits on incongruent trials were not ubiquitous. Goldfarb and Henik (2013) found that they were not present when lists were composed entirely of trials for which the word was irrelevant for responding (50 % neutral/50 % incongruent lists; Experiment 1) or when lists were mostly incongruent (Goldfarb & Henik, Experiment 2), even when cues were 100 % valid. It is not obvious why participants would not adopt an eye blurring or gaze aversion approach in these contexts. Second, we found that pre-cue benefits on incongruent trials were present only when participants had sufficient time to prepare (Experiment 1). If participants were simply blurring their eyes or averting gaze when a conflicting pre-cue was shown, it would not seem to require 2,000 ms to perform these strategies effectively. These findings cast doubt on the idea that eye blurring or gaze aversion strategies may be masquerading as proactive control in pre-cueing paradigms.[10]

[10] Consistent with this view, Raz et al. (2003) demonstrated that eye blurring is not an effective strategy for minimizing interference on incongruent trials in a non-pre-cueing Stroop paradigm. They also showed that, while gaze aversion is effective, it produces benefits on incongruent trials that are much larger (e.g., 109 ms speeding of RTs) than the largest pre-cue benefits observed on incongruent trials in the experiments in which proactive control was presumably operating.

Another possible explanation is that pre-cue benefits on incongruent trials reflect a general demand characteristic to respond quickly when subjects are reminded about the task. This view is difficult to reconcile, however, with the patterns we obtained across experiments. For example, we found that the pre-cue benefits on incongruent trials were restricted to the 2,000 ms CSI, selectively in the experiments in which an abstract proactive control setting was needed to achieve a benefit given the conditions of stimulus uncertainty (Experiments 1 and 4 but not Experiment 2; see also Goldfarb & Henik's, 2013, finding of selective pre-cue benefits on incongruent trials when most trials in list were neutral). If pre-cue benefits on incongruent trials have nothing to do with proactive control and are instead attributable to the demand characteristic, then pre-cue benefits should have emerged consistently across CSIs and across experiments (e.g., see Experiment 3 for the absence of a pre-cue benefit). Another telling pattern that calls into question the demand characteristic account is that pre-cue benefits on incongruent trials were not accompanied by high error rates, as one might expect if the pre-cues reminded participants to respond quickly without any influence of a control process (i.e., speed–accuracy tradeoff). Finally, the findings of Parris, Bate, Brown, and Hodgson (2012) are relevant to addressing this alternative account. They primed participants to respond quickly by presenting words such as "fast" and "hurry" for 100 ms prior to presentation of a Stroop stimulus. Participants were faster to respond to incongruent stimuli but not neutral stimuli or congruent stimuli, for which they were slowed. Critically, the time elapsing between the onset of the prime and the presentation of the Stroop stimulus was a mere 200 ms. This suggests that it does not take 2,000 ms to employ a strategy of responding more quickly—if the conflicting pre-cues in our study simply reminded participants to respond quickly, then pre-cue benefits should have been found even at the shortest (500 ms) CSI in Experiment 1.

Future considerations

An interesting question that has emerged from the present as well as some past findings (e.g., Correa et al., 2008) concerns why the pre-cue benefits on incongruent trials are not more robust under conditions of stimulus uncertainty where proactive control appears to be operating. One explanation is that consciousness (i.e., intentional; willed, voluntary; strategic adjustments) plays a less influential role in the control of attention than might be assumed (cf. Hommel 2007, 2013 for view that consciousness is not very useful for the control of action). The intrinsic demands of a task may have a bigger effect on performance than does voluntary effort (Kahneman, 1973). Relatedly, there may be certain interference resolution processes that can act only after the target of attentional biasing (e.g., the word to be ignored) is known (cf. Stokes, Thompson, Nobre, & Duncan, 2009). If so, there may inevitably be residual interference similar to the residual switch costs that are found when individuals prepare a task set (for review, see Kiesel et al., 2010).

Another explanation pertains to use of the 4-choice, 50 % congruent design, which tends to attract attention to the informative word. The conflicting pre-cues essentially encourage participants to filter out a dimension (i.e., word) that is generally informative (useful) (see Footnote 3; Algom, Dekel, & Pansky, 1996; Dishon-Berkovits & Algom, 2000; Melara & Algom, 2003; Sabri, Melara, & Algom, 2001). Pre-cue benefits may be larger when such tension is not present. For example, an ideal design for making words uninformative is the 2-choice, 50 % congruent design in which all responses are equally correlated with a given word (Melara & Algom, 2003). Indeed, when we used a conceptually similar design (Experiment 2), we found larger pre-cue benefits on incongruent trials. The dilemma is that such benefits likely reflected the efficacy of a primarily reactive attention-switching strategy and not proactive control.

Conclusion

To summarize, the current study provided novel and theoretically important evidence supporting the view that explicit, trial-by-trial congruency pre-cues produce variable effects on cognitive control. One such effect was that pre-cues facilitated engagement of a preparation-dependent proactive control mechanism that enhanced performance on incongruent trials under conditions of stimulus uncertainty. This finding provides support for the DMC account (Braver et al., 2007) in showing that control adjustments need not only be conflict-triggered (e.g., Botvinick et al., 2001) but can also occur prior to stimulus onset. However, pre-cues also produced effects on incongruent trials that were not preparation-dependent but rather, like pre-cue benefits on congruent trials, appear to be supported by strategies that are primarily reactive in nature such as attention switching (i.e., for purposes of predicting response associated with the irrelevant word; cf. Logan & Zbrodoff, 1982). Collectively, the findings support the view that expectations for interference (i.e., knowledge regarding congruency), though present in advance of stimulus onset, may affect performance via preparation-dependent proactive control or primarily reactive mechanisms.

Acknowledgments Julie M. Bugg, Department of Psychology, Washington University in St. Louis; Alicia Smallwood, Department of Psychology, DePauw University. We thank Nathaniel Diede and

Keith Hutchison for thoughtful comments on earlier versions of the manuscript, and Chelsea Birchmeier, Zunaira Komal, Henna Mishra, Simran Sahni, Bridgette Shamleffer, and Vivian Tao for assistance with data collection.

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