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BRIEF REPORT

Stroop proactive control and task conflict are modulated by concurrent working memory load

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Abstract Performance on the Stroop task reflects two types of conflict—informational (between the incongruent word and font color) and task (between the contextually relevant color-naming task and the irrelevant, but automatic, word-reading task). According to the dual mechanisms of control theory (DMC; Braver, 2012), variability in Stroop performance can result from variability in the deployment of a *proactive* task-demand control mechanism. Previous research has shown that when *proactive* control (PC) is diminished, both increased Stroop interference and a reversed Stroop facilitation (RF) are observed. Although the current DMC model accounts for the former effect, it does not predict the observed RF, which is considered to be behavioral evidence for task conflict in the Stroop task. Here we expanded the DMC model to account for Stroop RF. Assuming that a concurrent working memory (WM) task reduces PC, we predicted both increased interference and an RF. Nineteen participants performed a standard Stroop task combined with a concurrent *n*-back task, which was aimed at reducing available WM resources, and thus overloading PC. Although the results indicated common Stroop interference and facilitation in the low-load condition (zero-back), in the high-load condition (two-back), both increased Stroop interference and RF were observed, consistent with the model's prediction. These findings indicate that PC is modulated by concurrent WM load and serves as a common control mechanism for both informational and task Stroop conflicts.

Keywords Stroop · Working memory · Executive control · Task conflict · Dual mechanism of control

Cognitive control is a key human capacity that enables us to act in a goal-directed and flexible way, freeing us from the constraints of automaticity or stimulus bounds (Miller & Cohen, 2001; Miyake et al., 2000). For example, in the Stroop task (Stroop, 1935), participants are required to identify the color in which a color word is presented, while ignoring the word meaning. Since word reading is automatic, participants are faced with a need to inhibit the irrelevant words when they are incongruent with their font color (e.g., to respond red to GREEN written in red color). The Stroop interference—slower reaction times (RTs) for incongruent than for neutral stimuli (e.g., XXXX written in red)—and facilitation—faster RTs for congruent (e.g., RED written in red) than for neutral stimuli—effects are an indication of the fact that this selection is not perfect. Nevertheless, the low error rate in normal participants and the increased error rate in patient populations with executive and frontal deficits (Cohen & Servan-Schreiber, 1992) demonstrate the role of the frontal executive control system in mediating this top-down selection and suppressing automatic responses (Cohen, Dunbar, & McClelland, 1990). The role of the frontal executive system in Stroop top-down control is further supported by individual-

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differences studies that have demonstrated a correlation between the magnitude of the Stroop effect and working memory (WM) capacity—another important frontal function (e.g., Zhao et al., 2014)—as measured with the operation span task (Turner & Engle, 1989). Low-operation-span participants have longer RTs in incongruent Stroop trials (Kane & Engle, 2003; Meier & Kane, 2012), suggesting that the higher the WM capacity, the better one can perform the goal-relevant selection in the Stroop task.

Although these patient and individual-differences studies have provided strong support for the association between the frontal executive system that maintains and updates information in WM and Stroop interference, they do not establish causality. The aim of our study was to do just this, by probing the effect of a task manipulation that would reduce the available resources of the WM system on a concurrent Stroop task (see also de Fockert, Rees, Frith, & Lavie, 2001). For that purpose, we selected the *n*-back task—a task that involves both maintenance and updating components and is known to engage the frontal executive system (Owen, McMillan, Laird, & Bullmore, 2005). The *n*-back task was used as a concurrent task, with two levels: high versus low load. It was expected that under a high-load concurrent task (*two-back*), the executive resources would be occupied by maintenance and updating, allowing fewer resources to be allocated for Stroop control. It would appear, at a first glance, that reducing WM resources should mainly affect participants on the Stroop incongruent stimuli, since they would need more time to resolve the interference with fewer top-down resources. Although we endorse this prediction of increased Stroop interference (longer RTs for Stroop incongruent than for Stroop neutral stimuli; see also de Fockert et al., 2001), it only covers part of the story. We also predicted a reduced, or even reversed, Stroop facilitation (RF). To understand why reduced Stroop control would predict RF, we need to consider a novel theory of control—the dual control mechanism—and its relation to processing *task conflict*.

We first briefly review an influential computational framework of selective attention in the Stroop task, based on two types of control mechanisms (pro- and reactive) that we expand to account for task conflict, which allows us to outline our predictions for the present WM load manipulation. Then we present the experimental results and discuss their implications.

Task conflict and the dual-component control theory

According to the dual mechanisms of control theory (DMC) recently proposed by Braver (2012), selective attention has two components: *proactive* and *reactive*. As Braver has shown, this theory can account for a considerable degree of variability in the behavioral and imaging literature on executive control, as a result of the assumption that trials can vary with respect to the type of control process the participant employs. The idea is that participants can rely either on a *proactive* control (PC) mechanism (a top-down system) that projects to the relevant task dimension in advance of the stimulus presentation, or on a *reactive* one, which is only engaged as a result of conflict, when PC is missing. Variability in the Stroop task can then arise from variability in the deployment of PC, and this can vary with the task contingencies or with individual differences, or can just wax and wane spontaneously during a block of trials. A number of recent studies have highlighted a novel relation between variability in PC, the magnitude of Stroop facilitation, and the presence of task conflict.

Task conflict was first suggested by Goldfarb and Henik (2007) on the basis of an experiment that manipulated the degree of PC in a Stroop task. To reduce PC, they used a high frequency of neutral trials (Tzelgov, Henik, & Berger, 1992), together with prime cues that indicated that the coming trial was likely to contain (on 50 % of trials) nonneutral Stroop stimuli (congruent or incongruent) or neutral Stroop stimuli. A critical fraction (50 %) of nonneutral trials, however, were not preceded by such signals. This led participants to relax their PC when no cue was given, making them rely more on the reactive component. The result was not only increased Stroop interference, but also a reversed Stroop facilitation—that is, slower RTs for congruent than for neutral stimuli. A number of follow-up studies replicated this finding under various conditions (Kalanthroff, Goldfarb, & Henik, 2013; Kalanthroff, Goldfarb, Usher, & Henik, 2013; Kalanthroff & Henik, 2014). To understand the RF effect, we developed an explicit computational model of the Stroop task, labeled the *proactive-control/task-conflict* (PC-TC) model, which was inspired by the DMC framework (but see the Discussion section) and which can account for task conflict. This model is briefly presented in the supplemental materials (see also Kalanthroff, Davelaar, Henik, & Usher, in preparation). Here we highlight its operation and predictions.

The model follows previous connectionist Stroop models (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen et al., 1990; De Pisapia & Braver, 2006; see the supplement and the Discussion section for differences), assuming a set of task-control units that bias information processing toward the relevant task dimension; importantly, these task units are connected by bilateral connections to the input stimuli (see Fig. 1, left panel).

Under high-PC conditions, the effect of the bottom-up connections into the task demand units is negligible, since the active color-naming unit inhibits the competing word-reading unit, and thus we obtain the standard result: RTs are faster for congruent and slower for incongruent trials, as compared with neutral trials. Under low PC, however, the relevant task-control unit (color naming) is only weakly

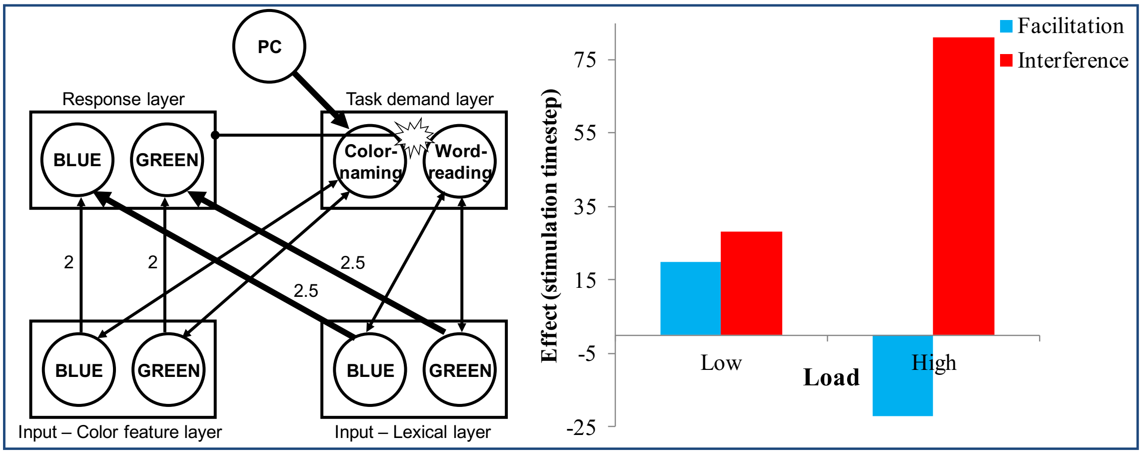

Fig. 1 Proactive-control/task-conflict (PC-TC) model. (Left) Schematic model demonstrating the work of two task-control units in the Stroop task that project and receive projections from sensory layers. Task conflict is represented by the flash event, and it inhibits the response units. The task-demand units are modulated by a proactive control (PC) circuit associated with the anterior cingulate (ACC; Botvinick et al., 2001). Here we do not implement the full ACC circuit (connecting the ACC with the response units), but only assume that a concurrent working memory task reduces the activation of the PC. (Right) Model predictions for facilitation and interference under low load (high PC) and high load (low PC); see also the supplemental materials

activated. In this situation, the bottom-up connection from stimuli to the task units triggers activation in those units. This is consistent with studies that have shown that stimuli can activate associated tasks (MacLeod & MacDonald, 2000; Rogers & Monsell, 1995). For neutral stimuli, only the color-task unit is activated, since there is a color but no word to read (e.g., XXXX). In both congruent and incongruent trials, however, both task-demand units are activated bottom-up. Thus, in the absence of strong inhibition from the color-demand unit (weak PC), the word-task unit is also activated, resulting in task conflict.[1] This is consistent with neuroimaging studies indicating that the anterior cingulate cortex (ACC)—a brain area thought to monitor conflict (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998)—is more activated in both congruent and incongruent conditions than in the neutral condition (e.g., Aarts, Roelofs, & van Turennout, 2009; Bench et al., 1993; Carter, Mintun, & Cohen, 1995). Finally, the model assumes that task conflict inhibits responses. This inhibition is maintained until the task conflict is resolved via reactive control, which is mediated by the weak PC representation biasing the competition between the task units in favor of the relevant task. The simulation illustrated in Fig. 1 (right panel) shows the model predictions under regular and reduced PC.

Under low-PC conditions, there is an increase in both the congruent and incongruent Stroop RTs, as compared with neutral trials. This is because only in these trial types is the response slowed down until the task conflict is resolved. This delay adds to the regular Stroop RT, resulting in an RF effect. To summarize, under a high concurrent WM load, which is expected to reduce PC, we predicted that we would find both increased Stroop interference and a reversed Stroop facilitation. This prediction was confirmed by the experimental data.

Method

Participants

Nineteen first-year psychology students (15 females and four males) of Ben-Gurion University of the Negev (Israel) participated for partial fulfillment of course requirements and credit. All participants had normal or corrected-to-normal vision, were right-handed, had no history of attention deficit or dyslexia, and were native speakers of Hebrew. Two participants were excluded from the analysis—one due to misunderstanding the instructions, and one due to having an error rate of more than 50 % for the *n*-back task (in both the low- and high-WM-load blocks). For the remaining 17 participants, the mean age was 23.06 years (*SD* = 1.09).

Stimuli

For the Stroop task, each stimulus consisted of one of four Hebrew color words— (blue), (red), (green), and (yellow)—or a four-letter string in Hebrew— (parallel to XXXX in the English version). The colors of the stimuli were red, blue, green, and yellow. We created four congruent, four neutral, and 12 incongruent combinations of colors and words, and the proportions of each congruency condition were equal. The words were presented at the center of a screen on a black background and were 0.98 in. high and 2.36 in. wide.

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[1] Following Botvinick et al. (2001), we computed task conflict as the multiplication of the activation (in the 0–1 interval) of the task units.

For the *n*-back task, six phonologically similar letters in English (B, D, G, P, T, and C) were used. The letters appeared in white on a black background in Times New Roman font, size 14.

Procedure

Data collection and stimulus presentation were controlled by a Dell OptiPlex 760 vPro computer with an Intel Core 2 duo processor E8400 3 GHz. The stimuli were presented on a Dell E198PF 19-in. LCD monitor. Participants sat approximately 23 in. away from the computer screen.

The experiment began with two practice blocks. The first block consisted of 12 key-matching practice trials in which a colored asterisk appeared at the center of the screen, three times in each of the four colors. Participants were instructed to respond to the color of the asterisks via the keyboard (keys were marked with colored stickers). The asterisk disappeared on a keypress or after 2,500 ms, and then the next trial began after a 1,200-ms interval. Feedback was given only for incorrect trials. The second practice block included 12 practice trials of the Stroop task (which were not analyzed further). Practice trials were identical to the experimental trials, with the differences being that only the Stroop task was presented (without the *n*-back task) and that feedback for accuracy and RT was given after each trial. Following the practice blocks, the combined Stroop and *n*-back task started (see the experimental task in Fig. 2).

Participants performed the two experimental blocks, high- and low-WM-load conditions, which were counterbalanced. Each experimental block included 18 practice trials (which were not analyzed further) and 180 experimental trials. For maximal randomization, we used sampling with replacement for the *n*-back letters, so each letter had an equal chance of appearing in any given trial. In the zero-back (low-WM-load) condition, participants were instructed to respond (by clicking the left shift key on the keyboard) only if the letter that was currently presented was identical to a specific target letter that was chosen randomly for each participant and that remained consistent throughout the entire block. In the two-back (high-WM-load) condition, participants were instructed to respond only if the letter that was currently presented was identical to the letter presented two trials earlier. The instructions emphasized accuracy and speed but stressed that accuracy was more important for the *n*-back task. For the Stroop task, participants were asked to respond according to the stimulus font color.

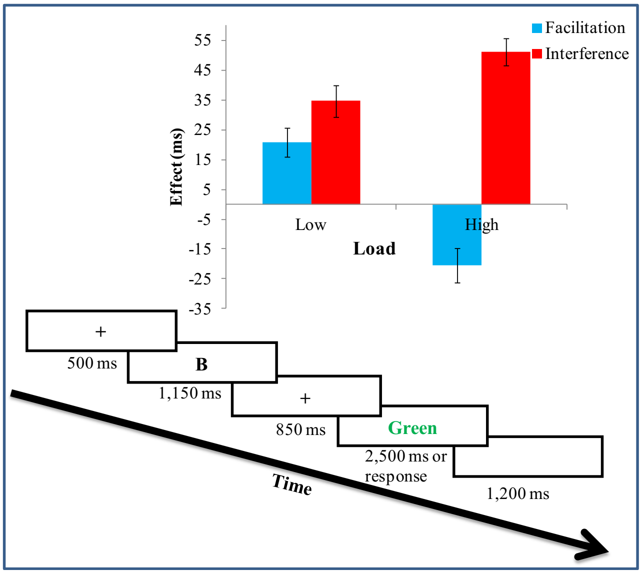

Fig. 2 Example of an experimental trial and the results of the concurrent Stroop and *n*-back tasks. Each trial began with a 500-ms fixation (a white plus sign in the center of a black screen), followed by a letter (the *n*-back task) for 1,150 ms (white letter in the center of a black screen). If a response was appropriate, participants were instructed to respond during this time. Then an 850-ms fixation point was presented, followed by a Stroop stimulus (appearing in the center of a black screen) for 2,500 ms or until response. Each trial ended with a 1,200-ms blank screen. The results showed facilitation (neutral RT minus congruent RT) and interference (incongruent RT minus neutral RT) for Stroop trials in both the low- and high-load conditions. Error bars represent one standard error from the mean (using Cousineau's, 2005, method to compute the error bars in within-subjects designs)

Results

For the *n*-back task, we calculated two separate accuracy rates: hits—the rate of correct response-to-target trials out of all targets—and correct rejections—the rate of correct no-response trials out of all trials in which there was no target. For the zero-back condition, the mean hit rate was .99, *SD* = .02, and the mean correct rejection rate was .9959, *SD* = .005. For the two-back condition, the mean hit rate was .66, *SD* = .11, and the mean correct rejection rate was .91, *SD* = .06. For the two-back condition, the rates were lower both for hits, $t(16) = 12{,}176$, $p < .001$, and for correct rejections, $t(16) = 5.571$, $p < .001$. This clearly shows that the two-back condition was more difficult, and hence caused a higher WM load. We show the Stroop mean RT for correct responses, as a function of concurrent WM load (low vs. high control) and congruency conditions in Table 1, and in terms of effects (facilitation and interference) in Fig. 2.

Table 1 Results of the combined *n*-back and Stroop tasks

	Congruent	Neutral	Incongruent
Low load	699 (29) [.96]	720 (31) [.96]	754 (28) [.96]
High load	881 (41) [.97]	861 (38) [.97]	912 (46) [.96]

Mean RTs in milliseconds (+standard errors of the means), and [accuracy rates] under the different load and congruency conditions of the combined *n*-back and Stroop tasks

In order to test whether the mean RTs were consistent with our model's predictions, a two-way analysis of variance (ANOVA) with repeated measures was applied to the RT data, with Congruency and Load as within-subjects factors. A significant interaction between congruency and load was found, $F(2, 32) = 6.592$, $p < .01$, $\eta_p^2 = .292$. Comparing the elongation in RTs in the congruent versus the incongruent conditions revealed no significant effect, $F(1, 16) = 2.983$, $p = .103$, $\eta_p^2 = .157$. Hence, the WM load manipulation did not have a differential effect on the two congruency conditions. Additionally, we found main effects for congruency, $F(2, 32) = 18.605$, $p < .001$, $\eta_p^2 = .538$, and for load, $F(1, 16) = 16.004$, $p < .001$, $\eta_p^2 = .5$, indicating generally longer RTs in the high-load condition. In order to further investigate the two-way interaction, we conducted two planned post-hoc analyses—a one-way ANOVA with repeated measures was applied to the RT data, with Congruency as a within-subjects factor, for each load condition separately. For the low-load condition, we found a significant effect of congruency, $F(2, 32) = 12.588$, $p < .001$, $\eta_p^2 = .44$. Planned comparisons revealed a significant congruency effect (i.e., incongruent RTs longer than congruent RTs), $t(16) = 5.073$, $p < .001$; a significant interference effect (i.e., incongruent RTs longer than neutral RTs), $t(16) = 2.169$, $p < .05$; and a significant facilitation effect (i.e., neutral RTs longer than congruent RTs), $t(16) = 2.8$, $p < .02$. These results are consistent with the common Stroop effect (MacLeod, 1991). For the high-load condition, we found a significant effect of congruency, $F(2, 32) = 13.68$, $p < .001$, $\eta_p^2 = .461$. Planned comparisons revealed a significant congruency effect, $t(16) = 2.915$, $p = .01$; a significant interference effect, $t(16) = 4.861$, $p < .001$; and most importantly, a significant reversed facilitation effect (i.e., congruent RTs longer than neutral RTs), $t(16) = 2.459$, $p < .03$. Overall, the results are consistent with our model's predictions.

Discussion

We carried out an experimental investigation of the role of proactive control (PC) in the Stroop task via a concurrent WM load (n-back) task. We reasoned that under a high-load concurrent task (two-back), participants would have their executive resources occupied by the maintenance and updating of the letters, allowing fewer resources to be allocated to the PC of the Stroop task. In a computer simulation model, the PC-TC manipulation was found to have a dual effect on Stroop RTs: an increase in Stroop interference and a reversal of Stroop facilitation. As we discuss in more detail in the supplement, the model differs in its implementation of reactive control from an earlier DMC model by De Pisapia and Braver (2006); our reactive control mechanism is mediated by the weak PC biasing the competition between the task-demand units (Fig. 1 left), rather than by the presence of fast (within the same trial) response conflict. This choice was motivated by our previous findings indicating that when PC is reduced, through manipulations of the Stroop task (e.g., warning cues or the frequency of neutrals), one finds task conflict, whose signature is an RF effect (e.g., Goldfarb & Henik, 2007; Kalanthroff, Goldfarb, & Henik, 2013; Kalanthroff, Goldfarb, Usher, & Henik, 2013). Accordingly, task conflict appears (and needs to be resolved) even in congruent Stroop trials, which have the lowest response conflict. Importantly, our model applies to Stroop tasks in which nonword neutral trials are used. The assumption that neutral trials do not activate the lexical pathway, bottom-up, corresponds to the use of nonword neutrals, and future work will be needed for testing the model's predictions on word neutral trials.

Although RF has been reported in a Stroop task before, this is the first study that has examined whether it depends on concurrent WM load—a more direct way to manipulate the degree of PC than manipulations of the Stroop factors (e.g., neutral frequency), which may have additional effects. Other frequency manipulations, such as an increase in the congruency proportion, do not reduce or reverse the facilitation score (Bugg, McDaniel, Scullin, & Braver, 2011). Although a number of previous studies have examined the effects of WM load in the Stroop task (see below), they did not report effects on the facilitation scores.

The result of our experiment reflected the model's predictions. In the low-load condition, we found the common Stroop effects—both interference and facilitation. Critically, however, under the high-load condition, we found increased interference and reversed facilitation. A somewhat similar conclusion was recently reported in a study that examined a concurrent WM manipulation using a Stroop task (Soutschek, Strobach, & Schubert, 2013). This study, which only used congruent and incongruent Stroop stimuli (thus, facilitation and interference components could not be evaluated), showed that under a high concurrent WM load ($n = 2$), there was a reduction in the Gratton effect (as compared with $n = 0$; Gratton, Coles, & Donchin, 1992); we did not find a Gratton effect even with low load, so we could not assess its reduction. However, as in our study, although the load increased RTs in both the congruent and incongruent trials, the total Stroop effect did not increase (Stroop effects: no load, 157 ms; two-load, 141 ms; Alexander Soutschek, personal communication, September 3, 2014). Because we used neutral Stroop stimuli as well, we were able to also determine that this effect was mediated by an increased interference and a reverse facilitation. The lack of an increase in the Stroop effect with load in both of these studies suggests that the time to resolve the task and the information conflict are subadditive (for incongruent stimuli, the slow-down was less than the sum of each task/information conflict alone), and thus that the two processes partially overlap. Future studies will be needed to better quantify the interaction between the task and informational conflict (see, e.g., de Fockert et al., 2001, for a different result in a face Stroop paradigm).

The results also confirm that task conflict manifests in the Stroop task not only in manipulations of neutral frequency and of cue signals, but also as a result of a concurrent WM load, which is widely assumed to share resources with proactive task control (Cohen & Servan-Schreiber, 1992). Task conflict between the relevant and irrelevant tasks is triggered by both congruent and incongruent stimuli (but not by neutral nonword stimuli[2]), reflecting the ability of stimuli to activate, bottom-up, strongly associated task sets that are irrelevant to the task at hand (Gibson, 1979; Makris, Hadar, & Yarrow, 2011; Rogers & Monsell, 1995). These results are consistent with the results of more recent studies on task conflict in the Stroop task. For example, David et al. (2011) found evidence from an event-related potential (ERP) study for the existence of task conflict in the Stroop matching task; and Steinhauser and Hübner (2009) showed an empirical dissociation between task conflict and response conflict in the Stroop task.

The results of our study show that task conflict appears under high but not under low WM load. As was first suggested by Goldfarb and Henik (2007), and was explicitly demonstrated in our model, under regular circumstances the PC quickly and efficiently eliminates the task conflict by increasing activation of the relevant task (i.e., color naming) and suppressing the activation of the irrelevant task (i.e., word reading). When the PC is reduced due to high concurrent load, both tasks are activated by congruent Stroop stimuli, causing a task conflict, which in turn results in reverse facilitation. Other studies recently demonstrated task conflict with participants (1) whose control capacity was not yet fully developed (La Heij, Boelens, & Kuipers, 2010) or (2) whose control was less efficient (Kalanthroff & Henik, 2013); (3) when PC was relaxed (Goldfarb & Henik, 2007; Kalanthroff, Goldfarb, Usher, & Henik, 2013); and (4) with clinical populations (specifically, patients with obsessive-compulsive disorder) whose control was deficient (Kalanthroff, Anholt, & Henik, 2014).

Future studies with additional manipulations of PC on normal participants, and on patient populations that are likely to suffer from PC deficits, will be important to fully understand the variability associated with control in the Stroop task, the emergence of task conflict, and the various reactive control mechanisms needed to regulate it.

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[2] When neutral noncolor words (e.g., *window*, *building*) are used, task conflict occurs in all three congruency conditions, and therefore no effects emerge (e.g., Goldfarb & Henik, 2007; Kalanthroff, Goldfarb, & Henik, 2013).

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