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The Interactive Effects of Listwide Control, Item-Based Control, and Working Memory Capacity on Stroop Performance

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Hypothesized top-down and bottom-up mechanisms of control within conflict-rich environments were examined by presenting participants with a Stroop task in which specific words were usually presented in either congruent or incongruent colors. Incongruent colors were either frequently (high contingency) or infrequently (low contingency) paired with the word. These items were embedded within lists consisting of either 100% congruent or 100% incongruent filler items to create mostly congruent or mostly incongruent lists. Results indicated a significant item-specific congruency effect, which was largest for high contingency responses and within mostly congruent lists. In addition, a significant listwide congruency effect was obtained, and this interacted with working memory capacity (WMC). There were larger listwide congruency effects for low WMC individuals. Finally, the pattern of Stroop interference across lists for low WMC individuals was dependent upon the congruency of the preceding trial. These results support multiple forms of cognitive control, as well as contingency learning, as mechanisms underlying proportion congruence effects in Stroop and other conflict tasks. These findings are interpreted within Braver, Gray, and Burgess's (2007) dual mechanisms of control theory.

Keywords: Stroop, working memory, proportion congruent, contingency learning

Attentional control refers to our ability to orchestrate thought and action in accord with internal goals and to use a goal to modulate competition between relevant and irrelevant information (Balota & Faust, 2001). This ability is often examined experimentally through use of congruency tasks (e.g., Stroop, Simon, & Eriksen flanker) in which one must respond only to relevant target information in a display while suppressing responses to irrelevant information. For instance, in the Stroop task (Stroop, 1935), participants must name the ink color of presented words while ignoring the words themselves. The irrelevant words can be congruent, incongruent, or unrelated to the appropriate color response. The typical finding is that participants are slower and less accurate in naming the ink color of incongruent words than neutral words and faster in naming the ink color of congruent words than neutral words (for a review, see MacLeod, 1991).

In Cohen, Dunbar, and McClelland's (1990) model (see also Cohen & Huston, 1994), interference in congruency tasks arises from conflicting responses generated by the relevant and irrelevant response processing pathways and greater conflict arises when the response generated via the irrelevant pathway is dominant (e.g., the word response in a Stroop task). To overcome such conflict, Cohen et al.'s model includes a task demand unit, thought to reflect top-down control, that increases activation for information within the task-appropriate pathway (e.g., color naming) and suppresses information from the inappropriate pathway. This task demand unit thus reflects the crucial role of attentional control in maintaining and utilizing task goals to bias responding toward appropriate stimulus dimensions.

Evidence for the necessity of attentional control in such conflict tasks has come from experiments finding group-based or list-based differences in performance. For instance, researchers have found increased congruency effects among clinical populations, such as patients with prefrontal cortex damage (Vendrell et al., 1995), individuals with attention deficit disorder (Grodzinsky & Diamond, 1992), and individuals diagnosed with Alzheimer's disease (Castel, Balota, Hutchison, Logan, & Yap, 2007; Hutchison, Balota, & Duchek, 2010). In addition to group differences, list-based differences in performance have been found, with larger congruency effects when the experimental list is made up of mostly congruent trials than of mostly incongruent trials (Gratton, Coles, & Donchin, 1992; Hommel, 1994; Logan & Zbrodoff, 1979). This listwide proportion congruence effect suggests that participants weigh information from the irrelevant pathway more heavily when it often predicts the correct response (i.e., mostly congruent lists).

To explain list differences, Cohen et al.'s (1990) model must assume that individuals utilize the task demand unit to a greater extent under mostly incongruent conditions. Botvinick, Braver, Barch, Carter, and Cohen (2001) provided such a modification to this model by including a conflict monitoring unit that is sensitive to the degree of conflict (i.e., cross talk from information derived via appropriate and inappropriate pathways) on any given trial (for an alternative conflict-dependent account, see Verguts & Notebaert, 2008). In the Botvinick et al. model, trials involving high conflict, such as incongruent trials, signal the task demand unit that

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more top-down control is needed. Increasing the frequency of such trials causes a cumulative increase in control over trials, enhancing the system's ability to produce appropriate responses. However, with mostly congruent lists such conflict occurs much less often, resulting in less control and more interference from word reading.

Kane and Engle (2003) provided a demonstration that group-based and list-based differences in interference may be interdependent. Across five experiments, little-to-no Stroop differences were demonstrated between individuals high versus low in working memory capacity (WMC) within mostly incongruent lists, yet significant differences were demonstrated within mostly congruent lists. The increased WMC differences within mostly congruent lists were most strongly reflected in interference errors and reaction time facilitation effects. Both of these processes presumably reflect a failure in goal maintenance in which participants accidentally default to word naming on a trial (see MacLeod, 1991). As argued by Botvinick et al. (2001), the increased frequency of conflict experienced during mostly incongruent lists provides constant external reminders of the task goal to name the color rather than the word. In contrast, under mostly congruent conditions, greater demand is placed upon working memory to actively maintain the goal across congruent (i.e., nonconflicting) trials (for a related finding, see Hutchison, 2007).

In summary, increasing the proportion of congruent items in a list (a) increases interference from word reading and (b) increases the need for attentional control to maintain and utilize the task goal across time. The need to maintain task demands internally over time under mostly congruent conditions explains why congruence effects are larger under such conditions, especially when they are measured in interference errors and facilitation effects and especially among those low in WMC.

Item-Specific Proportion Congruence

Jacoby, Lindsay, and Hessels (2003) recently introduced a new type of Stroop congruency manipulation, the results of which present a serious problem for top-down explanations of the listwide congruency effect. In their study, congruency was manipulated not across lists but rather across items. Jacoby et al. presented participants with six color words. Three words (e.g., *black, blue,* and *green*) were 80% incongruent, and three words (e.g., *red, yellow,* and *white*) were 80% congruent. This item-specific proportion congruence manipulation enabled them to maintain the overall listwide congruency at 50%. Because item presentation was randomized across trials, any difference in Stroop effects between mostly incongruent and mostly congruent items cannot be due a central task demand mechanism, as individuals would not know which type of item to expect prior to stimulus onset. Across three experiments, mostly incongruent items had a smaller Stroop effect than mostly congruent items. Because all earlier listwide manipulations had confounded listwide with item-specific congruency (i.e., items in mostly congruent lists are themselves mostly congruent), this result suggests that earlier listwide congruency effects may have been due to automatic processes occurring at the item level, rather than to a central top-down control mechanism.

Bugg, Jacoby, and Toth (2008) recently unconfounded listwide and item-specific proportion congruence to test the intriguing possibility that listwide effects are actually item-specific effects in disguise. In their study, Pair 1 items (e.g., *red* and *blue*) were 50% congruent and Pair 2 items (e.g., *green* and *white*) were either 25% congruent or 75% congruent. This allowed them to examine listwide effects in the Stroop task for Pair 1 items embedded in mostly congruent (.67) or mostly incongruent (.33) lists created by the mostly congruent or mostly incongruent Pair 2 items. They found only a nonsignificant (13 ms) listwide congruence effect for Pair 1 items, despite a significant (82 ms) item-specific congruency effect between the mostly congruent and mostly incongruent Pair 2 items, suggesting that previous listwide congruency demonstrations were likely caused by unintended item-specific effects within lists.

In contrast to top-down control, Jacoby et al. (2003) offered two possible automatic mechanisms flexible enough to account for item-specific congruence effects: item-specific control and associative learning. According to the item-specific control account, mostly incongruent words in the Stroop task can come to automatically trigger top-down suppression of word reading. Alternatively, according to the associative learning account, item-specific congruency effects emerge through the associative learning of specific stimulus–response (S–R) contingencies. In other words, participants learn to give a specific color response (e.g., "red") to a particular word (e.g., *blue*). Past research has provided some support for associative S–R learning (Musen & Squire, 1993; Purmann, Badde, & Wendt, 2009; Schmidt & Besner, 2008; Schmidt, Crump, Cheesman, & Besner, 2007; Wendt & Luna-Rodriguez, 2009) and for item-specific control accounts (Bugg, Jacoby, & Chanani, 2010).

As evidence for S–R learning, Musen and Squire (1993, see also Schmidt et al., 2007) presented color words in a specific incongruent color over several blocks. Participants demonstrated decreased reaction times (RTs) across blocks for these specific color–word combinations, but RTs increased when the words were paired with a different color on a final block. Moreover, this occurred despite chance performance on a recognition test in which participants were asked to indicate specific word–color pairings. Findings such as this prompted Blais, Robidoux, Risko, and Besner (2007) to modify the Botvinick et al. (2001) model to account for item-specific congruency effects by allowing conflict detection to strengthen activation only for the specific color predicted by the word, rather than color naming in general.

Bugg et al. (2010) argued that item-specific control also contributes to item-specific proportion congruency effects. However, in the standard Stroop task, participants are more likely to utilize S–R contingency learning, due to dimensional imbalance between words and colors (Melara & Algom, 2003), which make words more salient. Using a picture–word interference paradigm (i.e., name the picture and not the word), Bugg et al. attempted to shift participants' attention toward the relevant picture dimension as a cue to proportion congruency (rather than the irrelevant word) by (a) decreasing the size of the word relative to the picture, (b) increasing picture detail to avoid word "pop out," (c) varying word location, (d) making each picture more "surprising" by using a larger set size (four versions of each picture), and (e) manipulating proportion congruency more strongly across the picture dimension than the response-irrelevant word dimension (Experiment 2). In the final block of trials, Bugg et al. inserted transfer stimuli using new pictures from the same category as previously mostly congruent or mostly incongruent pictures and pairing them with words of opposite congruency (e.g., a mostly congruent picture paired with a mostly incongruent word). Bugg et al. found an item-specific congruency effect that was based upon proportion congruency of pictures rather than words. Moreover, because picture-response contingency in this task is 100% regardless of picture–word congruency, this item-specific effect could not have been due to response-contingency learning. Indeed, the item-specific control in Bugg et al.'s experiment may be an example of a more general *context-specific* control effect in conflict tasks (Crump, Gong, & Milliken, 2006; Crump & Milliken, 2009; Heinemann, Kunde, & Kiesel, 2009; Vietze & Wendt, 2009) in which proportion congruency effects are larger under certain contextual conditions (e.g., location, font, background) than others. Such context-specific proportion congruency effects are not caused by S–R learning, because the contextual cue is paired equally with all stimuli and all responses.

Current Study

The current experiment was designed to examine mechanisms underlying both item-specific and listwide congruency effects with the Stroop task. In previous item-specific congruency experiments, incongruent items were usually presented in one specific color (or two colors in Jacoby et al.'s Experiment 1; for an exception, see Bugg et al., 2010). The use of this procedure confounds contingency with proportion congruency (Schmidt & Besner, 2008) such that high contingency responses are incongruent with the word for the mostly incongruent items and congruent with the word for mostly congruent items. In the current experiment, to circumvent this problem, the three mostly congruent and three mostly incongruent items were paired with all six possible colors and the likelihood of specific word–color pairings was manipulated from within this set to create high contingency incongruent trials (e.g., the word *red* written in black ink) and low contingency incongruent trials (e.g., the word *red* written in yellow, blue, green, or white ink). If item-specific congruency effects are due to item-specific control, Stroop effects should be reduced for words (e.g., *red*) that are usually shown in incongruent colors, regardless of whether the incongruent response is a high contingency color (e.g., *black*) or a low contingency color (e.g., *yellow*). In contrast, if item-specific congruency effects are due to S–R contingency learning, Stroop effects should be reduced to a greater extent for trials involving the high contingency color.

As did Bugg et al. (2008), the current study unconfounded listwide and item-specific congruency to examine the possibility of simultaneous contribution of top-down and bottom-up control mechanisms. Although Bugg et al. found no effect of listwide congruency, there are four reasons to suspect that Bugg et al.'s null effect may have been a Type II error: (a) They tested only 18 young adults in their lists, limiting their statistical power to detect a difference between groups; (b) their within-subject item-specific congruency manipulation (75% vs. 25%) was stronger than their between-subjects listwide manipulation (67% vs. 33%); (c) they could only examine listwide effects among their 50% congruent items (i.e., Pair 1), which prevented examining potential Item-Specific × Listwide Congruency interactions; and (d) if listwide congruence effects are simply item-specific effects in disguise, rather than differences in goal maintenance across lists, then why do listwide congruence effects interact with WMC? Examination of Kane and Engle's (2003) data suggests that the performance of low span individuals was more dependent upon listwide congruency than was that of high span individuals. If it can be assumed that those Bugg et al. sampled (Washington University undergraduates) were mostly high in span, then their participants may have been less sensitive to listwide congruency effects.[1] As did those in Kane and Engle, participants in this experiment also received an operation span (ospan) measure of WMC (Unsworth, Heitz, Schrock, & Engle, 2005).

Method

Stimuli

The six color words used by Jacoby et al. (2003) were divided into three sets (*red* and *black, yellow* and *blue, green* and *white*). The first two sets served as critical items, and the color words *green* and *white* were filler items. Each word and each color were presented 30 times for each participant (see Table 1). Critical words in the mostly congruent set were presented in their own color on 20 trials (67%) and were presented twice in each of the five other possible incongruent colors (33%). Critical words in the mostly incongruent set occurred in their own color on 10 trials (33%) and in the incongruent colors on 20 trials (67%). Of importance, these 20 incongruent trials for each mostly incongruent word consisted of 16 trials in which it was presented in one specific color (the high contingency condition) and four trials in which it appeared in each of the other possible incongruent colors (the low contingency condition). For instance, when in the mostly incongruent condition, the word *red* was presented in red for 10 trials, was presented in black for 16 trials, and was presented once each in yellow, blue, white, and green. Assignment of critical color sets to the mostly congruent and mostly incongruent conditions was counterbalanced across participants.

Independently from the item-specific congruency (67% vs. 33%) manipulation, filler item congruency was manipulated between lists to create overall lists that were either mostly congruent (67%) or mostly incongruent (33%). These filler items were always congruent for the mostly congruent list, and they were always incongruent for the other two lists. For the mostly $\text{incongruent}_{\text{mixed}}$ list, the filler items were presented six times in each of the five possible incongruent colors, whereas for the mostly $\text{incongruent}_{\text{single}}$ group, the filler items were presented 30 times in the color of the alternate filler word (e.g., the word *WHITE* presented in green). These different mostly incongruent lists were used to examine the importance of total number of list S–R contingencies upon performance. The mostly incongruent mixed list contained more S–R parings, and the mostly incongruent single list matched the small number of S–R contingencies found in the mostly congruent list.

[1] Indeed, this assumption has recently been directly tested within the Semantic Priming Project (Hutchison et al., 2010). In this project, student participants from four universities (Montana State University; State University of New York at Albany; University of Nebraska, Omaha; Washington University in St. Louis) are tested in a large battery of tests that includes the automated operation span used in the current study as well as a Stroop task and an antisaccade task. Students from Washington University have significantly outperformed students from all three of the other institutions on all three of these attentional control tasks. In contrast, performance did not differ among the other three universities on any of the tasks. Thus, one can reasonably conclude that the population of Washington University students has a higher degree of attentional control than does that of MSU students.

Table 1
Frequency of Word–Color Pairings for Mostly Incongruent Items, Mostly Congruent Items, and Filler Items

		Color					
Item type	Sample word	Red	Yellow	Black	Blue	Green	White
Mostly incongruent	RED	10	1	**16**	1	1	1
Mostly congruent	YELLOW	2	20	2	2	2	2
Mostly incongruent	BLACK	**16**	1	10	1	1	1
Mostly congruent	BLUE	2	2	2	20	2	2
$Filler_{mixed}$	GREEN	6	6	6	6	0	6
$Filler_{mixed}$	WHITE	6	6	6	6	6	0
$Filler_{single}$	GREEN	0	0	0	0	0	30
$Filler_{single}$	WHITE	0	0	0	0	30	0
$Filler_{cong}$	GREEN	0	0	0	0	30	0
$Filler_{cong}$	WHITE	0	0	0	0	0	30

Note. Filler items are presented in all possible incongruent colors ($Filler_{mixed}$), one specific incongruent color ($Filler_{single}$), or a congruent color ($Filler_{cong}$). Congruent trials are shown on the diagonal for nonfiller words. Boldface type highlights high contingency incongruent responses for mostly incongruent items. Assignment of words to mostly congruent or mostly incongruent conditions was counterbalanced across participants.

Design

The current experiment utilized a 3 (list) × 2 (congruency) × 3 (item type) mixed design. Because contingency was manipulated only for incongruent trials, this manipulation was nested within the congruency manipulation. Congruency (congruent vs. incongruent) and item type (mostly congruent, mostly incongruent high contingency, mostly incongruent low contingency) were both manipulated within participants, and list (mostly congruent, mostly $incongruent_{mixed}$, mostly $incongruent_{single}$) was manipulated between participants.

Procedure

Stimuli were presented with E-prime software (Schneider, Eschman, & Zuccolotto, 2002), and responses were coded by a model 300 PST serial response box. Each individually tested participant was seated approximately 60 cm from a video graphics array monitor. Instructions were displayed on the monitor and paraphrased by the experimenter. Participants were instructed to name the ink color but not the word itself and to respond as quickly and accurately as possible. Participants received 180 total experimental trials. Each target word was presented centered in 18-point Courier New font on a gray background for 3,000 ms or until a response was given and was preceded by a 1,000-ms interstimulus interval. Trials were presented in a pseudorandom order. An experimenter sat next to the participant, held a sheet with the correct (color) responses for each trial, and coded the participant's responses as (a) correct response, (b) response error, or (c) microphone error with his or her right hand. Response errors consisted of responding with the wrong word (e.g., responding "green" to the word *GREEN* written in blue) or with a blended word (e.g., "gre-blue"). Experimental trials were preceded by 12 randomly presented practice trials in which the six words each occurred once in a congruent and an incongruent color.

The automated version of the operation span task (Unsworth et al., 2005) was included following the Stroop task. In this task, participants use their mouse to answer "true" or "false" to math problems (e.g., $2 \times 4 + 1 = 9$) as quickly as possible. After each response, they are presented with a letter for 800 ms to hold in memory. After three to seven sets of problems, they are presented with a 3 × 4 matrix of letters and asked to click on the presented letters in the order in which they were shown. An individual's overall score is the sum of all letters from sets in which all letters were recalled in the correct order. Unsworth et al. demonstrated that this version of ospan correlates well with other measures of WM capacity and has good internal consistency ($\alpha = .78$) and test–retest reliability (.83).

Participants

Two hundred and four male and female Montana State University undergraduates participated for a research requirement for an introductory psychology class. All were native English speakers with normal or corrected-to-normal color vision. However, the data from one student were excluded due to suspected color blindness. Data were also excluded from 13 participants who did not complete the ospan task and from eight participants (two in the mostly congruent list, four in the mostly incongruent mixed list, and two in the mostly incongruent single list) who made more than 40% errors in any condition, leaving data from a total of 182 participants. These included 68 in the mostly congruent list, 60 in the mostly incongruent single list, and 54 in the mostly incongruent mixed list.

Results

Only the critical mostly congruent and mostly incongruent items, which were identical across lists, were examined. Thus, any list differences in these analyses are not confounded by differences in item-specific congruency. Also, only correct responses were considered for the RT analyses. A separate mean and standard deviation were computed for congruent and incongruent stimuli for each participant. The modified nonrecursive outlier removal procedure, suggested by Van Selst and Jolicoeur (1994), removed

2.7%, 2.8%, and 2.9% of the correct RTs for participants in the mostly congruent, mostly incongruent mixed, and mostly incongruent single lists, respectively. Arithmetic means based on individual participants' trimmed mean RTs and errors are presented in Table 2.

Congruent Trials

RTs and errors to congruent trials were analyzed with two mixed analyses of variance (ANOVAs) with item type (mostly congruent vs. mostly incongruent) as a within-subject variable and list (mostly congruent, mostly incongruent mixed, mostly incongruent single) as a between-subjects variable. Overall RTs did not differ across lists ($F < 1$). An item-specific congruency effect was obtained, $F(1, 179) = 9.17$, $MSE = 536$, $\eta_p^2 = .05$, in which responding was faster for mostly congruent items than mostly incongruent items. However, this interacted with list, $F(2, 179) = 8.12$, $MSE = 536$, $\eta_p^2 = .08$. In particular, participants who received the mostly congruent or mostly incongruent single list were faster on mostly congruent items than mostly incongruent items; however, those who received the mostly incongruent mixed list showed a numerically (but not significantly) reversed pattern. This interaction with list suggests that item-specific differences on congruent trials depend upon the number of response contingencies present in the list. For error rates, there was a marginal item-specific congruency effect, in which participants responded more accurately to mostly congruent than mostly incongruent items, $F(2, 179) = 3.58$, $MSE = 3.2$, $\eta_p^2 = .02$.

Stroop Effects

RT difference scores for each participant between the three incongruent conditions and their respective congruent conditions were analyzed with the same mixed ANOVA used above. There was a main effect of list, $F(2, 179) = 12.01$, $MSE = 8{,}256$, $\eta_p^2 = .12$, such that Stroop effects for participants within the mostly congruent list were larger than for those in the two mostly incongruent lists. Stroop effects did not differ among those receiving the two mostly incongruent lists. This is the first listwide congruency demonstration not confounded by item-specific congruency differences. There was also a main effect of item type, $F(2, 358) = 44.89$, $MSE = 38$, $\eta_p^2 = .20$, with decreasing Stroop effects across mostly congruent items (132 ms), mostly incongruent low contingency items (112 ms), and mostly incongruent high contingency items (89 ms). The difference between mostly incongruent high and low contingency responses supports the role of S–R contingency learning in Stroop proportion congruence effects. In contrast, the difference between mostly congruent and mostly incongruent low contingency items could be due either to S–R contingency learning for mostly congruent items or to item-specific control on mostly incongruent low contingency items. Finally, there was a significant interaction between item type and list, $F(4, 358) = 6.02$, $MSE = 19$, $\eta_p^2 = .06$, due to larger item-specific congruency effects within the mostly congruent list than within the mostly incongruent lists. For those receiving the mostly congruent list, Stroop effects differed across all three item types. Participants in the two mostly incongruent lists showed smaller Stroop differences between mostly congruent items and mostly incongruent high contingency items and no difference between mostly congruent items and mostly incongruent low contingency items (both $ps > .05$), even when the data from both lists were combined ($p = .15$). When the interaction was examined from a different perspective, listwide proportion congruency effects were larger for mostly congruent items than for mostly incongruent items in both the high and the low contingency conditions. It is important to emphasize, however, that there were significant listwide effects on all three conditions, even though the proportion congruency for the critical items themselves was equal across lists.

Table 2
Mean Reaction Times and Percentage Errors for Mostly Congruent, Mostly Incongruent High Contingency, and Mostly Incongruent Low Contingency Items Presented in Congruent and Incongruent Color Naming Conditions in Mostly Incongruent or Mostly Congruent Lists

			Mostly incongruent items[a]					
	Mostly congruent items		High contingency				Low contingency	
List and condition	*M* (*SE*)	% error (*SE*)	*M* (*SE*)	% error (*SE*)	*M* (*SE*)	% error (*SE*)	*M* (*SE*)	% error (*SE*)
Mostly congruent list								
Incongruent	787 (13)	10.5 (0.9)	733 (13)	7.2 (0.8)			765 (13)	9.6 (1.2)
Congruent	612 (10)	0.5 (0.2)			631 (11)	0.6 (0.3)		
Stroop effect	175*	10.0*	102*	6.6*			134*	9.0*
Mostly incongruent list, mixed fillers								
Incongruent	738 (15)	4.6 (1.0)	703 (14)	4.6 (0.9)			729 (15)	3.2 (1.3)
Congruent	626 (11)	0.1 (0.2)			621 (12)	0.7 (0.3)		
Stroop effect	112*	4.5*	82*	3.9*			108*	2.5*
Mostly incongruent list, single fillers								
Incongruent	712 (14)	7.3 (0.9)	693 (13)	6.4 (0.8)			706 (14)	7.0 (1.2)
Congruent	602 (11)	0.6 (0.2)			611 (12)	1.1 (0.3)		
Stroop effect	110*	6.7*	82*	5.3*			95*	5.9*

[a] There is no high or low contingency response for a mostly incongruent item when presented in the congruent condition.
* $p < .05$.

In error rates, there was again a significant effect of listwide congruency, $F(2, 179) = 11.09$, $MSE = 101$, $\eta_p^2 = .11$, with Stroop effects decreasing across the mostly congruent (8.6%), mostly incongruent single (6.0%), and mostly incongruent mixed lists (3.6%). There was also again a main effect of item type, $F(2, 358) = 3.65$, $MSE = 38$, $\eta_p^2 = .02$. Across groups, the Stroop effect was significantly larger for mostly congruent items than for mostly incongruent high contingency items and marginally ($p > .08$) larger than for mostly incongruent low contingency items, and there was no difference between the high and low contingency mostly incongruent items. The interaction between item type and list congruency did not reach significance ($p > .14$).

WMC

Stroop effects for high span participants and low span participants (highest and lowest 25%, respectively) were examined in a 2 × 2 × 3 mixed ANOVA with list (mostly congruent list vs. collapsed mostly incongruent lists) and item type as within-subject factors. These data are presented in Figure 1. Overall, there were larger Stroop effects for low span than high span participants in both RTs and error rates, as confirmed by a main effect of WMC: $F(1, 82) = 21.42$, $MSE = 5{,}996$, $\eta_p^2 = .21$; $F(1, 82) = 7.24$, $MSE = 119$, $\eta_p^2 = .08$, for RTs and error rates, respectively. This WMC difference interacted with list significantly in RTs, $F(1, 82) = 6.51$, $MSE = 5{,}996$, $\eta_p^2 = .07$, and marginally in error rates, $F(1, 82) = 3.31$, $MSE = 119$, $\eta_p^2 = .04$. In particular, the WMC difference in the mostly congruent list was greater than the nonsignificant overall WMC differences in the mostly incongruent lists. This pattern replicates Kane and Engle's (2003) WMC × List Proportion Congruency interactions, even when item-specific congruency effects are controlled. In error rates, there was also a marginal WMC × Item Type interaction, $F(2, 164) = 2.53$, $MSE = 39$, $\eta_p^2 = .03$. When examined separately, low span participants showed a significant item-specific congruency effect, $F(2, 76) = 4.53$, $MSE = 33$, $\eta_p^2 = .11$, with more errors to mostly congruent items than to the high and low contingency mostly incongruent items, whereas high WMC individuals did not ($F < 1$, $\eta_p^2 = .00$). This marginal interaction also reflected the finding that WMC differences were significant for mostly congruent items, marginal for mostly incongruent high contingency items, and nonsignificant for mostly incongruent low contingency items.

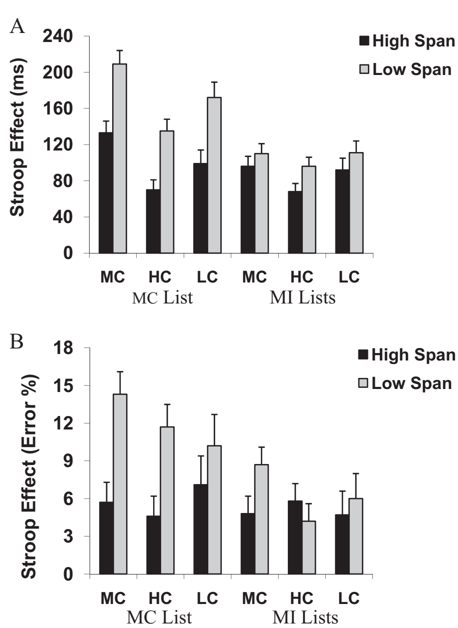

Figure 1. Mean Stroop effects for high and low span participants for mostly congruent, mostly incongruent high contingency (HC), and mostly incongruent low contingency (LC) items within mostly congruent (MC) or mostly incongruent (MI) lists.

In addition to the extreme-groups analysis, correlations between ospan and Stroop performance for each item type were conducted using all participants. These results complemented those obtained in the quartile split analysis. For those in the mostly congruent list, negative correlations between WMC and Stroop effects were significant across all three item types in RTs ($r = -.39$, $r = -.40$, $r = -.39$ for mostly congruent, mostly incongruent high contingency, and mostly incongruent low contingency items, respectively) and for two out of three item types in error rate ($r = -.28$, $r = -.33$, $r = -.11$, respectively). In contrast, the only correlation between Stroop effects and ospan among the two mostly incongruent lists was for errors to mostly congruent items, which was marginal for the mostly incongruent mixed list ($r = -.26$, $p < .06$) and significant for the mostly incongruent single list ($r = -.32$, $p < .02$). In addition, the item-specific congruency effect in error rates (larger Stroop effect for mostly congruent than mostly incongruent items) was negatively correlated with ospan ($r = -.32$, $p < .04$).

These correlational findings utilizing all participants support the claims that (a) mostly congruent lists require greater attentional control to maintain the goal of naming colors (and suppressing word reading) throughout the task and (b) low WMC individuals had larger item-specific proportion congruence effects in error rates than did high WMC individuals. The same pattern of correlations occurred when using *z*-transformed RTs (rather than raw RTs) that control for individual differences in baseline RT.

Sequential Effects

A post hoc analysis was conducted of previous trial type (congruent vs. incongruent) along with item type and list to examine the potential trial-to-trial adjustments in control predicted by Botvinick et al.'s (2001) model.[2] Immediate exact repetitions of stimuli were removed prior to analysis to avoid immediate repetition priming effects. These data are shown in Table 3 and are presented separately for high and low WMC individuals, although this initial analysis includes data from all individuals.

Replicating results of past studies (e.g., Gratton et al., 1992), there was a main effect of previous trial (the so-called Gratton effect) in the error analyses, $F(1, 179) = 10.63$, $MSE = 150$, $\eta_p^2 = .06$, with greater Stroop effects following congruent trials than incongruent trials. Surprisingly, however, there was no Gratton effect on Stroop RTs ($F < 1$), although there was a Previous Trial × List interaction in RTs, $F(1, 175) = 4.96$, $MSE = 5{,}868$,

[2] For brevity, in this analysis the mostly $\text{incongruent}_{\text{single}}$ and mostly $\text{incongruent}_{\text{mixed}}$ groups were collapsed.

Table 3
Mean Stroop Effects in Reaction Times and Percentage Errors After Previous Congruent and Incongruent Trials for High and Low WMC Individuals Responding to Mostly Congruent, Mostly Incongruent High Contingency (HC), and Mostly Incongruent Low Contingency (LC) Items Presented in Mostly Congruent (MC) or Mostly Incongruent (MI) Lists

	Item type							
	Overall		Mostly congruent		Mostly incongruent HC		Mostly incongruent LC	
Condition and list	*M* (*SE*)	% error (*SE*)	*M* (*SE*)	% error (*SE*)	*M* (*SE*)	% error (*SE*)	*M* (*SE*)	% error (*SE*)
Previous congruent trial								
Low WMC								
MC list	163 (14)	14.2 (2.3)	196 (19)	18.1 (2.9)	150 (19)	13.4 (2.5)	143 (21)	11.3 (3.9)
MI list	131 (11)	6.9 (1.8)	107 (15)	8.4 (2.3)	153 (15)	7.1 (1.9)	134 (17)	5.3 (3.0)
List effect	32	7.3*	89*	9.7*	−3	6.3*	9	6.0
High WMC								
MC list	111 (13)	7.2 (2.0)	139 (17)	6.9 (2.6)	85 (17)	6.5 (2.2)	110 (19)	8.2 (3.4)
MI list	90 (10)	6.0 (1.7)	85 (14)	6.1 (2.2)	98 (14)	8.0 (1.9)	86 (16)	4.0 (2.9)
	21	1.2	54*	0.8	−13	1.5	24	4.2
Previous incongruent trial								
Low WMC								
MC list	194 (15)	8.2 (2.0)	218 (17)	8.2 (2.3)	179 (18)	12.0 (2.4)	184 (31)	4.4 (4.3)
MI list	100 (12)	6.9 (1.6)	105 (14)	8.9 (1.8)	95 (14)	3.0 (1.8)	100 (24)	8.7 (3.4)
List effect	94*	1.3	113*	−0.7	84*	9.0*	84*	−4.3
High WMC								
MC list	87 (14)	4.5 (1.8)	112 (16)	3.8 (2.0)	68 (16)	0.3 (2.1)	81 (28)	9.5 (3.8)
MI list	89 (12)	4.4 (1.5)	91 (13)	4.3 (1.7)	72 (13)	5.5 (1.8)	104 (23)	3.5 (3.2)
List effect	−2	0.1	21	−0.5	−4	−5.2	−23	6.0

Note. These data are collapsed across the mostly incongruent, mixed filler and mostly incongruent, single filler lists.
* $p < .05$.

$\eta_p^2 = .03$, with a greater listwide proportion congruent effect following incongruent trials. It is important to note, however, that listwide differences, although reduced, were also significant following congruent trials and that the interaction in error rates (though not significant) was in the opposite direction, with a larger listwide effect following congruent trials. Thus, the listwide congruency effect occurred following either congruent or incongruent trials and was therefore not completely driven by trial-to-trial adjustments in control. No other effects were significant.

A final four-way ANOVA was conducted in which WMC was added as a fourth variable to examine whether WMC differences across item types and lists depended upon whether previous trials were congruent or incongruent. In error rates, there were no significant interactions involving WMC and previous trial (ps $>$ .15). In contrast, for RTs, there was a significant Previous Trial × List × WMC interaction, $F(1, 80) = 9.50$, $MSE = 5{,}690$, $\eta_p^2 = .11$. As can be seen in the Overall column in Table 3, individuals high in WMC showed no significant listwide effects regardless of previous trial type, whereas low WMC individuals showed a larger listwide proportion congruence effect in RTs following incongruent trials (a significant 94-ms difference) than following congruent trials (a marginal 32-ms difference). However, it should be noted that the pattern in error rates was in the opposite direction, with low WMC individuals showing a marginally greater listwide proportion congruence effect following congruent trials (a significant 7.3% difference) than following incongruent trials (a nonsignificant 1.3% difference). This pattern is discussed in greater detail in the Discussion section. No other effects approached significance.

Discussion

The current study produced eight novel findings that should enhance our understanding of the interplay between top-down and bottom-up mechanisms of control during conflict tasks. First, the current study is the first to produce both listwide and item-specific proportion congruency effects. Second, the reduction in Stroop effects across all three lists for high contingency relative to low contingency responses demonstrated that the bulk of the item-specific congruency effect was produced by S–R contingency learning between the distractor words (e.g., *red*) and their frequently associated response (e.g., *black*). This finding is consistent with Besner and colleagues' (Blais et al., 2007; Schmidt & Besner, 2008; Schmidt et al., 2007) contingency account of item-specific proportion congruency effects and also with Bugg et al.'s (2010) prediction that item-specific effects rely more on contingency learning than on item-specific control in the standard color–word Stroop task.

Third, item-specific differences on congruent trials occurred only in the two lists with a limited number of S–R contingencies. This lent credence to the intuitively plausible hypothesis that number of response alternatives influences the ease in which participants learn S–R contingencies.

Fourth, this is the first demonstration of listwide congruency effects that are not confounded with item-specific effects. Therefore, listwide effects are not always simply item-specific effects in disguise. This supports attentional control accounts of listwide congruency effects (Botvinick et al., 2001; Cohen et al., 1990), in which the frequent conflict encountered within mostly incongruent lists serves as an external cue to reinforce the task goal of suppressing word reading and enhancing color naming.

Fifth, the current study obtained a Listwide × Item-Specific Proportion Congruency interaction, indicating that top-down control and incidental contingency learning are not independent. List-based differences in congruency effects were strongest for mostly congruent items, and item-based control of responding (mostly through S–R contingency learning) was greatest under mostly congruent lists. The larger listwide effect for mostly congruent items may partially explain the null listwide congruency effect by Bugg et al. (2008), as they examined listwide effects only among their 50% congruent items. In addition, the reduction of listwide congruency effects for mostly incongruent items suggests that reductions in interference from word reading could be produced via either top-down attentional control or bottom-up S–R contingency learning. Such a *redundancy* model, in which multiple processes improve performance, predicts the type of underadditive Listwide × Item-Specific Congruency interaction observed in this experiment. Because both processes affect word interference, there is little benefit from having both present (e.g., mostly incongruent items within mostly incongruent lists) but a large cost if both are absent (e.g., mostly congruent items within mostly congruent lists).

Sixth, the current study replicated Kane and Engle's (2003) finding of greater WMC differences in Stroop effects under mostly congruent lists while controlling for item-specific proportion congruency and for the congruency of the preceding trial. This further supports the attentional control account of listwide congruency effects. In particular, the increase in Stroop effects under mostly congruent conditions occurs mostly among low WMC individuals, in whom prolonged internal goal maintenance is deficient (Kane, Bleckley, Conway, & Engle, 2001). This WMC × Listwide Congruency interaction also partially explains Bugg et al.'s (2008) null effect because they tested Washington University undergraduates, most of whom were likely high WMC individuals who are less sensitive to manipulations of list proportion congruency.

Seventh, the current study demonstrated that item-specific proportion congruency effects in error rates are also greater for low WMC individuals. This was demonstrated both by a marginal WMC × Item Type interaction using the quartile split and by a significant correlation between WMC and item-specific Stroop effects when all participants were included. This finding suggests that, during conflict tasks, low WMC individuals are more prone to S–R contingency learning between the irrelevant dimension (e.g., word) and its frequently associated response. This intriguing finding will be elaborated in greater detail below.

Finally, examination of preceding trials demonstrated that listwide proportion congruence effects were larger following incongruent trials in RTs but numerically larger following congruent trials in error rates. Moreover, the Previous Trial × List interaction further interacted with WMC in RTs, such that the increase in listwide effects following incongruent trials occurred only for low span individuals and high span individuals showed no significant list-based proportion congruence effects regardless of preceding trial. Again, however, low span individuals showed the opposite pattern in error rates, with significant listwide effects only following congruent trials. This pattern fits well with Kane and Engle's (2003, see also Spieler, Balota, & Faust, 1996) account of Stroop performance, in which (a) successful responding requires both goal maintenance and response competition resolution and (b) low WMC individuals are presumably impaired in both processes, relative to high WMC individuals. Accordingly, if the goal to name colors (and suppress word reading) is active immediately prior to stimulus onset, Stroop effects manifest primarily in interference RTs, as participants attempt to resolve the competition between conflicting word and color responses on incongruent trials. However, if the goal is neglected, Stroop effects manifest primarily in error rates, as participants accidentally produce the incorrect word response (presumably) before the response conflict is detected. The data from low WMC individuals in the mostly congruent list thus fit very well with this account. Previous congruent trials should increase the chance of goal neglect (and increased Stroop in errors), whereas previous incongruent trials should lead to goal retrieval (and increased Stroop in RTs).

The current results fit fairly well with Braver, Gray, and Burgess's (2007) proposed proactive and reactive mechanisms of cognitive control. In that model, proactive control involves sustained activity within lateral prefrontal cortex (PFC) to maintain task goals in preparation of future events. Such control is ideal for early selection of task-appropriate information over distracting information. However, this mechanism is metabolically taxing, requires high WMC, and is less sensitive to changes in stimulus contingencies, because the system is biased to attend selectively to goal-relevant information while ignoring goal-irrelevant stimulus features.

In contrast, reactive control is governed by transient activation within anterior cingulate cortex (ACC) after stimulus onset. The conflict between competing responses detected by ACC triggers other brain structures (e.g., lateral PFC, medial temporal lobe) to retrieve the inactive task goal from memory. Such reactive control does not require high WMC, is beneficial when conflict is infrequent, and increases control only following the rare incongruent trials.

De Pisapia and Braver (2006) provided evidence for differential engagement of proactive and reactive control mechanisms. Using functional magnetic resonance imaging, they found evidence of sustained lateral PFC activation (indicative of proactive control) for participants in mostly incongruent lists and of transient ACC (indicative of reactive control) for participants in mostly congruent lists.

The implications of these control mechanisms for item-specific and listwide congruency effects in conflict tasks are clear. Proactive control, if engaged, involves maintaining task goals over trials to enhance early selection of task-appropriate stimuli. This early selection decreases interference from irrelevant stimuli (e.g., words) and, in turn, reduces learning of S–R contingencies along this irrelevant dimension. However, only high WMC individuals can engage in proactive control over extended durations (i.e., within mostly congruent lists). In contrast, reactive control involves retrieving (rather than maintaining) goals triggered by current trial response conflict. This leads to enhanced performance on the next trial, which fades following each nonconflicting trial. The greater the number of nonconflicting trials, the less top-down control is exerted and the more word reading causes interference. This late-selection mechanism occurs after word reading has taken place, allowing for greater incidental learning of S–R associations.

The combination of Braver et al.'s (2007) dual mechanisms of control and Kane and Engle's (2003) goal-maintenance and response competition theories explains the current data reasonably well. If it is assumed that high WMC individuals are more likely to rely on proactive control regardless of list context, this would explain their relative insensitivity to listwide proportion congruency and previous trial congruency. In contrast, if it is assumed that low WMC individuals (a) are deficient in goal maintenance and response competition resolution and (b) rely more heavily on reactive control regardless of list, this would explain why they are more sensitive to differences in listwide, item-specific, and previous trial manipulations of congruency. For item-specific effects, reactive control should cause the irrelevant word dimension to be processed at a deeper level, which would facilitate S–R contingency learning. For listwide and sequential effects, reliance on reactive control would lead to fewer trial-to-trial corrections under mostly congruent lists, in which incongruent trials are less frequent. Moreover, once these corrections are made following the infrequent incongruent trials, low span individuals would still show larger Stroop interference in RTs, due to less efficient response competition resolution.

Although I believe the combination of these theories explains the data well, there are undoubtedly some results that are inconsistent with this explanation. For example, why do high and low WMC individuals show similar-sized item-specific proportion congruence effects when only RTs are examined? Equal- sized RT effects suggest that high span individuals also learn the S–R contingencies but correct for this biasing effect prior to responding. This is inconsistent with an early selection proactive control mode that blocks irrelevant stimuli from accessing attention and instead suggests that learning of such contingencies may occur automatically regardless of control setting. It is hoped that future studies will clarify this and other potentially incompatible results in this complex set of findings.

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