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Multiple levels of control in the Stroop task

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Multiple levels of control may be used in service of reducing Stroop interference. One is list-wide, whereby interference is reduced strategically in lists that include disproportionately more incongruent trials. A second, item-specific control is observed when proportion congruence is manipulated at the level of items. Item-specific control reduces interference for mostly incongruent relative to mostly congruent items. First, we show that item-specific control may drive both list-wide and item-specific proportion congruence effects (Experiment 1). We then show that item-specific control affects Stroop interference similarly when a single feature (a word) as opposed to a feature combination (a word + font type) signals proportion congruence (Experiment 2). Although this suggests that font type offers little advantage for controlling Stroop interference beyond the word, a novel, font-specific proportion congruence effect is observed in Experiment 3, indicating that font type can be used to control interference. These findings support the idea that multiple levels of control are used in reducing Stroop interference.

The Stroop color-naming task (Stroop, 1935) is well suited for evaluating flexibility in the control of cognitive processes and behavior. In the congruent condition of the task, stimulus word matches stimulus color (e.g., BLUE in blue ink) and participants may rely on well-learned reading processes to produce fast and accurate responding. In the incongruent condition, in contrast, accurate responding requires participants to use cognitive control mechanisms to dampen word reading and activate color-naming processes. The additional time that is taken to name the ink color in the incongruent relative to the congruent condition is referred to as *Stroop interference*. Although the task might seem relatively simple, the literature is replete with reports of robust Stroop interference effects (for a review, see MacLeod, 1991). Close to 1,000 articles have been published on the topic, yet the control mechanism(s) used to dampen word reading and activate color-naming processes remain to be fully explicated.

A complicating (or revealing, as we will argue) factor is the different instantiations (e.g., blocked conditions vs. intermixed trials) of the Stroop color-naming task appearing in the literature. Different task contexts appear to elicit different forms of cognitive control, precluding a unitary account of control mechanisms. *Proportion congruence* is one prominent factor that influences the control mechanisms that are adopted within a given task. Traditionally, proportion congruence is manipulated at a list-wide level by disproportionately presenting congruent and incongruent trials within a list. Participants can use frequencies to predict what type of trial is most likely to occur next, and control processes can be biased toward (as in a mostly congruent list) or away from (as in a mostly incongruent list) word reading prior to stimulus onset on the basis of these expectancies. Such contexts seem to induce a preparatory, goal-driven control mechanism that is implemented in a sustained fashion across trials (i.e., the bias toward or away from word reading remains constant throughout a list), analogous to the proactive control mechanism recently posited in the dual-mechanisms-of-control account (Braver, Gray, & Burgess, 2007). In contrast, in other task contexts, congruent and incongruent trials occur equally often within a list, and one is unable to anticipate the upcoming trial type and prepare control processes accordingly. These contexts demand a more flexible control mechanism that is capable of modulating word-reading and color-naming processes in a transient fashion on a trial-by-trial basis. Because such modulation occurs after stimulus onset, such a control mechanism must operate rapidly.

By this analysis, different cognitive control mechanisms underlie Stroop performance. One control mechanism appears to operate slowly and strategically at a list level, acting prior to stimulus onset. A second appears to operate rapidly at a trial or item-specific level, and acts after the stimulus has been presented. This conception of there being two distinct levels of control may be misleading, however, because these mechanisms largely have been uncovered in independent lines of investigation. In Experiment 1, we simultaneously investigate these two putative control mechanisms. There are at least two possibilities for their interplay. One is that both mechanisms exert observable influences on the magnitude of Stroop interference across different levels of proportion congruence (e.g., mostly congruent, mostly

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incongruent, or 50/50 contexts). Alternatively, a single level of control may underlie completely the differences in the magnitude of Stroop interference across different levels of proportion congruence. Next, we develop these ideas.

List-Level Control

The list-wide proportion congruence effect refers to the attenuation of Stroop interference that is observed in a mostly incongruent relative to a mostly congruent context (e.g., list, block, or condition) (see, e.g., Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Logan, Zbrodoff, & Williamson, 1984; Lowe & Mitterer, 1982; Shor, 1975; Tzelgov, Henik, & Berger, 1992). The list-wide proportion congruence effect is attributed most commonly to task strategies or to cognitive control settings that uniformly modulate the degree to which word reading and color naming influence performance in a particular context. In the mostly incongruent condition, control is believed to operate in a goal-driven fashion, strategically reducing the influence of the word prior to stimulus onset. In contrast, in the mostly congruent condition, word reading is permitted largely to govern behavior, because word reading is facilitative on the dominant trial type. In this condition, incongruent stimuli are unanticipated and produce greater conflict upon onset than do the same stimuli in the mostly incongruent condition (e.g., Carter et al., 2000). These dynamics produce prolonged reaction times (RTs) for incongruent items and greater Stroop interference in the mostly congruent context.

Item-Level Control

An alternative explanation of the list-wide proportion congruence effect refers to item-specific control.[1] This explanation is supported by a recent study in which it was shown that proportion congruence effects occur at the level of particular items (Jacoby, Lindsay, & Hessels, 2003). In their study, Jacoby et al. (2003) assigned color-word sets composed of two to three items to either a mostly incongruent condition (e.g., BLACK, BLUE, and GREEN) or a mostly congruent condition (e.g., RED, YELLOW, and WHITE). Seventy percent of the time, each item (e.g., BLUE) in the mostly incongruent condition occurred in an incongruent color from that set (e.g., black or green), and 30% of the time it appeared in the congruent color (blue). The proportions were reversed for the mostly congruent items, such that RED, for example, appeared 70% of the time in red ink and 30% of the time in yellow or white ink. Jacoby et al. (2003) observed an item-specific proportion congruence effect, whereby Stroop interference was attenuated for the items (e.g., BLACK, BLUE, and GREEN) that were mostly incongruent relative to the items (e.g., RED, YELLOW, and WHITE) that were mostly congruent. Critically, the item-specific proportion congruence effect occurred in a list-wide context wherein trial type was unpredictable because congruent and incongruent trials occurred equally often and were intermixed randomly. This suggests that the locus of the item-specific proportion congruence effect resides not in control strategies based on learned frequencies or expectancies regarding the upcoming trial type. A single word-reading policy per list, whereby participants decide to use or avoid using word information, is ineffectual when participants do not know what type of trial will occur next. Rather, the item-specific proportion congruence effect appears to reflect control at the time of stimulus onset. How might an item-specific control mechanism account for list-wide proportion congruence effects?

For purpose of exposition, consider a typical list-wide proportion congruence experiment in which 70% of trials are congruent and 30% of trials are incongruent. The standard procedure is to design the lists in a manner that holds constant the list-wide proportion congruence level for each item in the stimulus set (e.g., BLUE, GREEN, and RED). Seventy percent of BLUE, GREEN, and RED trials appear in their congruent ink color, and 30% appear equally often in one of the two incongruent ink colors. As such, variations in list-wide proportion congruence are confounded perfectly with variations in item-specific proportion congruence. The implication is that specific items (i.e., words), rather than lists in general, could be associated with particular congruence proportions. This raises the question as to whether list-wide proportion congruence effects are really item-specific effects in disguise.

Additional theorizing also has addressed the interplay between list- and item-specific levels of control in the Stroop task and has questioned whether list-wide proportion congruence has any influence on performance. For example, Blais, Robidoux, Risko, and Besner (2007) recently modified the classic conflict-monitoring model of Botvinick, Braver, Barch, Carter, and Cohen (2001). Rather than implementing control at the pathway (color-naming) level on the basis of the detection of conflict, Blais et al. implemented control at an item level. In their model, the detection of conflict served to strengthen the association between the color-naming pathway and a specific color rather than color naming in general, as in the Botvinick et al. model. Simulations showed that this new model accounted for both the list-wide and item-specific proportion congruence effects, whereas the prior model fell short in accounting for the latter. Together with the findings of Jacoby et al. (2003), such modeling raises the possibility that a control mechanism that operates at the item-specific level can alone account for list-wide proportion congruence effects. Alternatively, as noted above, both list-level and item-specific control may be operative in a single task context (e.g., a mostly incongruent list), but existing designs may mask their separate contributions.

EXPERIMENT 1

Experiment 1 tested these possibilities by isolating the list-wide effects from the item-specific influences. This was achieved by using two pairs of color words. One pair (e.g., RED and BLUE) always had an equal number of congruent and incongruent trials—that is, an item-specific proportion congruence level of 50%. A second pair (e.g., GREEN and WHITE) had either a high or a low proportion of congruent trials. More specifically, the item-specific proportion congruence (PC) of the second pair was either 75% or 25%. Presenting the first pair (i.e., 50% item-specific PC) with either the item-specific PC-75 pair or the item-specific PC-25 pair together in a mixed list produced list-wide proportion congruence equal to 67% and 33%, respectively. The primary question of interest was whether Stroop effects for the item-specific PC-50 items would change as a function of the list-wide proportion congruence set by the item-specific PC-75 and item-specific PC-25 items. Such a result would support the existence of a list-level control mechanism because no item-specific influence is expected to be operating when item-specific PC is 50%. Alternatively, no change in Stroop effects for the item-specific PC-50 items as a function of list-wide proportion congruence would indicate an absence of list-wide control. If Stroop effects differ for the item-specific PC-75 and item-specific PC-25 items, then this suggests that an item-specific control mechanism is operative.

A second question of interest concerned the effects of age on list-wide and item-specific control. Past studies indicate that the magnitude of slowing on incongruent relative to congruent trials tends to be larger for older adults and that this pattern does not simply reflect generalized slowing (e.g., Brink & McDowd, 1999; but see Verhaeghen & De Meersman, 1998, for an alternative view). The reason for this increase in Stroop interference is debated. Some researchers suggest that it reflects an age-related deficit in cognitive control related to inhibitory processes (Spieler, Balota, & Faust, 1996) or goal maintenance (De Jong, Berendsen, & Cools, 1999). Little is known, however, about the effect of proportion congruence manipulations on older adults' Stroop performance. Mutter, Naylor, and Patterson (2005) found that interference was greater in a mostly congruent as compared with a mostly incongruent list for both younger and older adults. West and Baylis (1998) found that age differences in Stroop interference were limited to a mostly incongruent block, with older and younger adults showing similar Stroop effects in a mostly congruent block of the task. The authors attributed this pattern to older adults' difficulty in actively maintaining the color-naming goal to strategically guide task performance in the mostly incongruent block. In other words, older adults were purported to have a deficit in proactively implementing a list-wide form of control. If strategic control processes such as active goal maintenance underlie list-wide proportion congruence effects and older adults are impaired relative to younger adults in implementing these control processes, then one should expect age-related differences in how Stroop effects are modulated by list-wide proportion congruence, as evaluated by performance on the item-specific PC-50 trials in the present experiment. To our knowledge, item-specific proportion congruence effects have not been investigated in an older adult population, and therefore it is not clear whether older adults will be disadvantaged at implementing item-specific control on the item-specific PC-25 and PC-75 trials. Examining possible age effects on list-wide and item-specific proportion congruence may be revealing as to the mechanisms underlying these manipulations.

Method

Participants. Thirty-six young (18–23 years; $M = 19.9$) and 36 older (67–87 years; $M = 74.8$) adults participated in the experiment. The young adults were undergraduate students at Washington University and participated for course credit. The older adults were from the Washington University Older Adult Participant Pool and were each paid $5. All participants were native English speakers with normal color vision and normal or corrected-to-normal visual acuity. A random half of the participants from each age group were assigned to each level of the between-subjects factor, list-wide proportion congruence.

Design and Materials. Four color-words and their corresponding colors were divided into two pairs (RED and BLUE, GREEN and WHITE). Words from one pair (e.g., RED and BLUE) served as item-specific proportion congruency PC-50 items for which an equal number of congruent and incongruent trials were presented; thus, the item-specific PC was 50%. Words from the other pair (e.g., GREEN and WHITE) served as item-specific PC-25 or item-specific PC-75 items for which either a low or high proportion of congruent trials, respectively, were presented. When mixed with the item-specific PC-50 items, the item-specific PC-25 items produced a list-wide PC of 33%. Similarly, the item-specific PC-75 items produced a list-wide proportion congruence of 67% when mixed with the item-specific PC-50 items. This list-wide proportion congruence manipulation was between participants, with 18 young and 18 older adults assigned randomly to the 33% and 67% list-wide PC conditions. The frequencies of the different stimulus types are given in Table 1. In addition to incongruent and congruent trials, 32 neutral trials were also presented. Neutral trials consisted of eight instances of each of the four colors, presented as strings of percent signs. Word pairs were counterbalanced across participants such that each word served equally often as item-specific PC-50 or item-specific PC-25/PC-75 items. The test list of 320 trials was separated into four blocks of 80 trials, with each block presenting one quarter of all possible word/color combinations. Presentation order within a block was randomized for each participant. The experiment was programmed in E-Prime 1.1, with words presented in E-Prime's standard color palette ("red," "blue," "green," and "white") in 24-point Arial font positioned in the center of the screen against a light gray ("silver") background.

Procedure. The experiment was conducted in a small room with the experimenter present. Participants were told that words or percent signs would be presented in the center of the screen and that their task was to name the color in which each stimulus was presented as quickly and accurately as possible. After completing 12 practice trials (one of each of the eight possible word/color combinations along with 4 neutral trials), participants performed four blocks of 80 trials, taking short breaks between each block. For each trial, a single stimulus was presented in the center of the screen and remained visible until a vocal response was detected, at which point the stimulus was erased. The experimenter entered the participant's response via keyboard. Trials on which the voice key was tripped by extraneous noise or imperceptible speech were coded as scratch trials. One second later, the next stimulus was presented. The entire procedure took about 25 min.

Table 1
Frequencies of the Word/Color Combinations in the List-Wide PC-33 and List-Wide PC-67 Conditions of Experiment 1

		Color			
Condition	Word	Red	Blue	Green	White
List-wide PC-33	RED	24	24	0	0
	BLUE	24	24	0	0
	GREEN	0	0	24	72
	WHITE	0	0	72	24
List-wide PC-67	RED	24	24	0	0
	BLUE	24	24	0	0
	GREEN	0	0	72	24
	WHITE	0	0	24	72

Note—List-wide PC-33 and PC-67 refer to a list-wide proportion congruency of 33% or 67%. In the example above, the words RED and BLUE are serving the role of item-specific PC-50 items, and the words GREEN and WHITE are serving the role of item-specific PC-25 and PC-75 items.

Table 2
Mean Reaction Times (RTs, in Milliseconds) for Item-Specific PC-50, PC-25, and PC-75 Trials in Experiment 1

	Congruent		Incongruent		Stroop Effect	
	M	*SE*	*M*	*SE*	*M*	*SE*
Young						
IS PC-25 & LW PC-33	611	19	671	22	60	13
IS PC-50 & LW PC-33	618	20	693	20	75	12
IS PC-50 & LW PC-67	629	25	717	26	88	17
IS PC-75 & LW PC-67	591	18	734	28	142	15
Old						
IS PC-25 & LW PC-33	752	35	872	36	120	19
IS PC-50 & LW PC-33	765	32	925	45	160	26
IS PC-50 & LW PC-67	766	32	929	36	163	20
IS PC-75 & LW PC-67	714	26	952	38	238	21

Note—IS, item-specific; LW, list-wide; PC, proportion congruence, with the number referring to the proportion of congruent trials. Stroop effect = RT(incongruent) − RT(congruent).

Results

For each participant, RTs less than 200 msec and greater than 3,000 msec were removed, which eliminated fewer than 1% of the trials for both the young and older adults. Results reported as statistically significant reached at least the .01 alpha level, except where noted.

RT. Mean RTs for item-specific PC-50, PC-25, and PC-75 trials are presented in Table 2. There were two sets of critical analyses. In the first, we analyzed performance on the item-specific PC-50 trials to determine whether Stroop effects were influenced by list-wide proportion congruence. A $2 \times 2 \times 2$ mixed ANOVA was conducted with trial type (congruent vs. incongruent) as a within-subjects factor and list-wide proportion congruence (list-wide PC-33 vs. list-wide PC-67) and age (young vs. old) as between-subjects factors. As expected, RTs were slower for incongruent than for congruent trials [$F(1,68) = 157.14$, $MS_e = 3{,}388.02$], older adults were slower than younger adults [$F(1,68) = 38.65$, $MS_e = 30{,}809.81$], and the magnitude of slowing on the incongruent trials relative to the congruent trials was larger for older adults [$F(1,68) = 17.17$, $MS_e = 3{,}388.02$]. Most importantly, the list-wide proportion congruence manipulation and all interactions involving this factor were not significant (Fs < 1), suggesting that list-wide proportion congruence did not affect Stroop performance. In particular, the nonsignificant interaction between list-wide proportion congruence (33% vs. 67%) and trial type (congruent vs. incongruent) indicated that Stroop effects were almost identical for item-specific PC-50 items in the list-wide PC-33 and list-wide PC-67 conditions. This was the case for both the young adults (Ms = 75 vs. 88 msec, respectively) and older adults (Ms = 160 vs. 163 msec, respectively) (Fs < 1). Given the possibility that participants may have become more sensitive to the list-wide proportion congruence manipulation in the latter blocks of the task, we reconducted the analyses above separately for each half of the task. The results from the first half and second half were identical to the patterns reported above.

Given that list-wide proportion congruence had no significant effect on the magnitude of Stroop interference, we then analyzed the item-specific PC-25 and item-specific PC-75 trials to determine whether performance was affected by item-specific proportion congruence. A $2 \times 2 \times 2$ mixed ANOVA was conducted with trial type (congruent vs. incongruent) as a within-subjects factor and item-specific proportion congruence (item-specific PC-25 vs. item-specific PC-75) and age (young vs. old) as between-subjects factors. RTs were slower for incongruent than for congruent trials [$F(1,68) = 262.70$, $MS_e = 2{,}689.53$], older adults were slower than younger adults [$F(1,68) = 39.12$, $MS_e = 26{,}844.40$], and the magnitude of slowing on the incongruent trials relative to the congruent trials was larger for older adults [$F(1,68) = 20.29$, $MS_e = 2{,}689.53$]. Most critically, there was strong evidence of an item-specific proportion congruence effect. The Stroop effect increased reliably from the item-specific PC-25 condition ($M = 89$ msec) to the item-specific PC-75 condition ($M = 190$ msec) [$F(1,68) = 33.66$, $MS_e = 2{,}689.53$]. Although the increase was larger for older adults (120 to 238 msec) than for younger adults (60 to 142 msec), the three-way interaction was not significant [$F(1,68) = 1.12$, $p = .29$]. As with the list-wide proportion congruence manipulation, the effects of the item-specific manipulation and all interactions involving this factor did not change as a function of experience (first half vs. second half) with the task.

To verify that this pattern of findings did not change when log-transformed RTs were used to account for differences in baseline response latency, we repeated the analyses above. The pattern of results was identical.[2]

Error rate. Mean error rates for item-specific PC-50, PC-25, and PC-75 trials are presented in Table 3. The analyses of error rate mirror those reported above for RT, focusing first on the effects of list-wide proportion congruence. The $2 \times 2 \times 2$ mixed ANOVA indicated that error rates were higher for incongruent ($M = .03$) than for congruent ($M = .004$) trials [$F(1,68) = 32.65$, $MS_e = .001$] and higher for younger adults ($M = .03$) than for older adults ($M = .01$) [$F(1,68) = 5.05$, $MS_e = .001$]. Most importantly, the list-wide proportion congruence manipulation and all interactions involving this factor were not significant

Table 3
Mean Error Rates for Item-Specific PC-50, PC-25, and PC-75 Trials in Experiment 1

	Congruent		Incongruent		Stroop Effect	
	M	*SE*	*M*	*SE*	*M*	*SE*
Young						
IS PC-25 & LW PC-33	.009	.003	.023	.004	.013	.006
IS PC-50 & LW PC-33	.004	.002	.045	.010	.041	.010
IS PC-50 & LW PC-67	.009	.004	.044	.011	.035	.010
IS PC-75 & LW PC-67	.002	.001	.065	.016	.063	.016
Old						
IS PC-25 & LW PC-33	.000	.000	.013	.003	.013	.003
IS PC-50 & LW PC-33	.002	.002	.024	.008	.022	.008
IS PC-50 & LW PC-67	.002	.002	.024	.013	.022	.013
IS PC-75 & LW PC-67	.001	.001	.023	.005	.022	.005

Note. IS, item-specific; LW, list-wide; PC, proportion congruence, with the number referring to the proportion of congruent trials. Stroop effect = error rate(incongruent) − error rate(congruent).

(Fs < 1), suggesting that list-wide proportion congruence did not affect error rate. Consistent with the RT analysis, the nonsignificant interaction between list-wide proportion congruence (33% vs. 67%) and trial type (congruent vs. incongruent) indicated that the Stroop effect in error rate was almost identical for item-specific PC-50 items in the list-wide PC-33 and list-wide PC-67 conditions. This was the case for younger and older adults.

The effects of the list-wide proportion congruence manipulation were then examined separately for the first and second halves of the task. The entire pattern of findings was consistent with the combined block analysis reported above, except that the main effect of age was not significant [$F(1,68) = 1.61, p = .21$] during the first half of the task.

To examine whether item-specific proportion congruence had an effect on error rate, a 2 × 2 × 2 mixed ANOVA was again conducted, this time focusing on the item-specific PC-25 and item-specific PC-75 trials. Error rates were higher for incongruent trials ($M = .03$) than for congruent trials ($M = .003$) [$F(1,68) = 38.11$, $MS_e = .001$], younger adults ($M = .03$) made more errors than did older adults ($M = .01$) [$F(1,68) = 11.87$, $MS_e = .001$], and the relatively larger error rate on incongruent relative to congruent trials was larger for younger adults [$F(1,68) = 5.22$, $MS_e = .001$, $p = .03$]. These main effects were qualified by several interactions. Critically, there was strong evidence of an item-specific proportion congruence effect in error rate. The significant two-way interaction between item-specific proportion congruence and trial type indicated that the Stroop effect in error rate was smaller for the item-specific PC-25 condition ($M = .01$) than for the item-specific PC-75 condition ($M = .04$) [$F(1,68) = 10.83$, $MS_e = .001$]. Furthermore, the three-way interaction was also significant [$F(1,68) = 5.00$, $MS_e = .001$, $p = .03$], indicating that the difference in the magnitude of the Stroop effect between the item-specific PC-25 and PC-75 conditions was greater for younger (Ms = .01 vs. .06) than for older (Ms = .01 vs. .02) adults. Examining the age groups separately, 2 × 2 mixed ANOVAs indicated that the item-specific proportion congruence × trial type interaction was significant for younger [$F(1,34) = 8.59$, $MS_e = .00$] but not for older [$F(1,34) = 2.52, p = .12$] adults.

When the effects of the item-specific manipulation were examined separately for the first and second halves of the task, the pattern of findings was identical to that reported above for the combined block analysis, with a few exceptions. The main effect of group ($p = .06$), age × trial type interaction [$F(1,68) = 1.23, p = .27$], and age × trial type × item-specific proportion congruence interaction [$F(1,68) = 2.04, p = .16$] were not significant during the first half.

Discussion

The results of Experiment 1 suggest that an item-level control mechanism influenced the magnitude of Stroop interference such that interference was smaller for the mostly incongruent items. A critical question is whether a list-level control mechanism was also operative. The results strongly suggest that it was not, because list-wide proportion congruence had no effect on the magnitude of Stroop interference. This novel finding is contrary to several past reports (e.g., Logan et al., 1984; Lowe & Mitterer, 1982). The primary difference between the present study and studies such as these that demonstrated a list-wide proportion congruence effect is the design. Past studies perfectly confounded the list-wide manipulation with an item-specific manipulation. Here, we manipulated list-wide proportion congruence while holding item-specific proportion congruence constant. This approach allowed us to evaluate the distinct contributions of list-level and item-level control. The finding that item-level control exerted a significant influence on Stroop performance, but that list-level control did not, calls into question the locus of list-wide proportion congruence effects in previous studies. What formerly has been described as a list-wide control mechanism may actually be control that is operating on an item-by-item basis.

The analyses of age effects were also informative. Like the younger adults, older adults' Stroop performance (RT and error rate) was not affected by the list-wide proportion congruence manipulation. In contrast, for RT, older adults' Stroop performance *was* significantly modulated by item-specific proportion congruence in a manner that was comparable to the modulation observed for younger adults. That is, older adults' Stroop interference, like that of younger adults, was smaller for the mostly incongruent as compared with the mostly congruent items. This novel observation suggests that older adults are sensitive to proportion congruence manipulations when they are implemented at the level of particular items.

The item-specific proportion congruence effect was age invariant for RT, but not for error rate. For younger adults, the item-specific proportion congruence effect was large and reliable. However, for older adults, the smaller Stroop effect in error rate in the mostly incongruent (item-specific PC-25) relative to the mostly congruent (item-specific PC-75) condition was not statistically reliable. A survey of the means from the critical cells indicates that younger and older adults had similar error rates in the mostly incongruent condition (1%), but younger adults' error rates in the mostly congruent condition (6%) were inflated relative to older adults' error rates (2%). Thus, although both groups appear to exploit item-specific proportion congruence similarly in reducing Stroop interference in RT, there does appear to be an age difference in the degree to which item-specific proportion congruence affects error rate. Focusing solely on younger adults' performance, what differs between the mostly congruent and mostly incongruent conditions are error rates on the incongruent trials, not error rates on the congruent trials. Inflated error rates on the incongruent trials in the mostly congruent condition most likely reflect prediction errors, whereby participants emit the most frequent (but incorrect) response for a particular word. It is reasonable to assume that such prediction errors are correlated positively with the strength of the association between stimuli (words) and responses, and that younger adults would have stronger representations of this association relative to older adults. By this account, the observed age difference is precisely as expected. Additionally, the observed trend ($p = .10$) for younger adults' Stroop effect in error rate to be magnified in the mostly congruent condition in the second relative to the first block, as associations are presumably strengthened, is consistent with this account. We further consider the contribution of stimulus–response learning and other mechanisms to the item-specific proportion congruence effect in the experiments that follow.

The findings of Experiment 1 have important theoretical implications. Typically, the list-wide proportion congruence effect has been attributed to a single color-naming or word-reading policy that is applied uniformly and strategically to all stimuli within a particular condition (list). For instance, computational modeling traditionally has focused on stronger weighting of the color-naming (goal) pathway in the mostly incongruent condition as the primary locus of the list-wide proportion congruence effect (e.g., Botvinick et al., 2001; Cohen, Dunbar, & McClelland, 1990). The findings of Experiment 1 provide potential difficulties for this view. Our findings instead suggest that a model with a control mechanism that operates at a single level is sufficient as long as that level is item specific and not list wide. Accordingly, Blais et al. (2007) demonstrated that a model that varies control at an item-specific level, by strengthening the connection between the color-naming pathway and a trial-specific response, can accommodate both item-specific and list-wide proportion congruence effects.

The findings of Experiment 1 also converge with prior research using the process-dissociation procedure (Jacoby, 1991). This procedure yielded stronger estimates of the word-reading process for mostly congruent than for mostly incongruent lists (Lindsay & Jacoby, 1994) and for mostly congruent than for mostly incongruent items (Jacoby et al., 2003). In both cases, variations in the word-reading process occurred independently of color naming, and color naming did not vary as a function of list-wide or item-specific proportion congruence. These studies, like the present experiment, imply that a similar control mechanism acts on the word-reading process to produce list-wide and item-specific proportion congruence effects.

Although a theoretical account of Stroop performance that entails a single item-level control mechanism is intriguing, the possibility remains that there are additional, yet undiscovered levels at which control is implemented. In Experiment 2, we pursued the general question of whether participants exploit several features that are available to control word reading in the Stroop task (i.e., use multiple levels of control) or tend to rely on a single level of control that leads to efficient performance.

EXPERIMENT 2

In Experiment 1, and in prior studies examining item-level control (e.g., Jacoby et al., 2003), item-specific proportion congruence was manipulated at the level of word. That is, particular words were grouped together in sets (pairs or triplets), and particular word sets were composed of mostly congruent or incongruent items. As such, particular words were predictive of the likelihood that an item was congruent or incongruent. This item-specific manipulation may encourage use of the word as a "feature" that directs control of the word-reading process on an item-by-item basis.

Similarly, word reading might be controlled on the basis of other features if they too were predictive of proportion congruence. For instance, participants may be capable of extracting low-level, perceptual features of Stroop stimuli (e.g., shapes of particular letters, certain letter combinations, or distinctive font types) that are predictive of (correlated with) proportion congruence. These features then might be used to exert rapid control over the word reading process, such that word reading is permitted to influence performance to varying degrees depending on the specific features of the present item.

In the following experiment, we investigated whether control can operate via multiple levels in the Stroop task. We did this by combining the item-specific manipulation, whereby proportion congruence was manipulated at the level of particular color-word pairs (e.g., BLUE and YELLOW are mostly congruent items and GREEN and WHITE are mostly incongruent items) with a proportion congruence manipulation based on a specific perceptual feature, font type. In one condition, the mostly congruent words appeared in one font type (e.g., Arial), and the mostly incongruent words appeared in a second font type (e.g., Bookman Old Style). We refer to this condition as the *multiple-features* condition, because particular words and particular features (e.g., BLUE and YELLOW in Arial font) were correlated simultaneously with a proportion congruence level (e.g., mostly congruent). In contrast, in a single-feature condition, proportion congruence was manipulated only at the level of particular color-word pairs. In this condition, the mostly congruent and mostly incongruent words occurred equally often in both font types, and therefore only a single feature, color word, was predictive of proportion congruence.

As demonstrated previously (Experiment 1; Jacoby et al., 2003), the manipulation of item-specific proportion congruence at the level of word pairs is expected to produce an item-specific proportion congruence effect, such that interference is greater for mostly congruent than for mostly incongruent word pairs. This effect should occur in the multiple- *and* single-feature conditions, because both include the item-specific proportion congruence manipulation. The critical question is whether multiple features that are related to proportion congruence can be used simultaneously to control word reading. If participants in the multiple-features condition exploit both the word itself and the font type in service of control over Stroop interference, then the item-specific proportion congruence effect should be magnified in the multiple- relative to the single-feature condition. More precisely, the magnitude of interference should be smaller for mostly incongruent items and larger for mostly congruent items in the multiple-features condition.

Method

Participants. Forty Washington University students participated in partial fulfillment of course credit or in exchange for monetary compensation. All participants were native English speakers between the ages of 18 and 25. Older adults did not participate in this or the subsequent experiment.

Design and Materials. Four color words and their corresponding colors were divided into two pairs (BLUE and YELLOW, GREEN and WHITE). Words from one pair (e.g., BLUE and YELLOW) were designated mostly congruent (80%), and words from the other pair (e.g., GREEN and WHITE) were mostly incongruent (80%). The two word pairs combined to produce 50% congruent and 50% incongruent trials at the list level.

In the multiple-features condition, the mostly congruent items appeared in one font type (e.g., Arial) and the mostly incongruent items appeared in the second font type (e.g., Bookman Old Style). As a consequence, two features (color word and font type) were correlated with proportion congruence. These features were counterbalanced across participants (n = 20), such that all possible combinations of font type and color-word pair occurred equally often at each level of proportion congruence. The single-feature condition was identical to the multiple-features condition, with the exception that font type was not correlated with proportion congruence. Rather, items from a particular color-word pair (e.g., BLUE and YELLOW) occurred equally often in both font types. The assignment of word pair to proportion congruence was counterbalanced across participants (n = 20). The single- versus multiple-features manipulation was carried out between subjects. Participants were assigned randomly to each condition.

Procedure. The procedure was identical to that of Experiment 1, except as noted below. There were 16 practice trials and two blocks of 108 test trials. The practice trials preserved the proportion congruence manipulation that was implemented in the test trials.

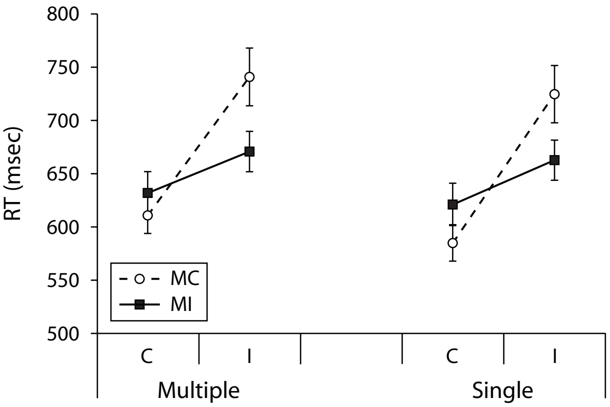

Figure 1. Mean reaction time (RT, in milliseconds) as a function of trial type (C = congruent, I = incongruent) and proportion congruence (MC = mostly congruent, MI = mostly incongruent) for the multiple- and single-feature conditions in Experiment 2.

Results

For each participant, RTs less than 200 msec and greater than 3,000 msec were removed. This resulted in the elimination of fewer than 1% of the trials from both the multiple- and single-feature conditions. Overall, errors were low (<1.3%). There were no significant effects in the analysis of error rates other than the finding that more errors were made on incongruent (M = 2.1%) than on congruent (M = 0.4%) trials [$F(1,38) = 15.14$, $MS_e = .00$, $p < .01$]. Therefore, to conserve space, we report only the analysis of correct RTs.

A 2 × 2 × 2 mixed-subjects ANOVA was conducted, with condition (multiple features vs. single features) as a between-subjects factor and proportion congruence (mostly congruent vs. mostly incongruent) and trial type (congruent vs. incongruent) as within-subjects factors. Incongruent trials (M = 700) were responded to more slowly than congruent trials (M = 612) [$F(1,38) = 214.26$, $MS_e = 1{,}439$]. The proportion congruence × trial type interaction indicated a significant item-specific proportion congruence effect [$F(1,38) = 74.29$, $MS_e = 1{,}195$]. As expected, the magnitude of Stroop interference was smaller for the mostly incongruent condition (M = 41) than for the mostly congruent condition (M = 135). As can be seen in Figure 1, the item-specific proportion congruence effect was observed in both the multiple- and single-feature conditions. Importantly, the absence of a significant three-way interaction indicated that the magnitude of the item-specific proportion congruence effect did not vary as a function of whether multiple features or a single feature was correlated with proportion congruence ($F < 1$).

Discussion

The findings of Experiment 2 provide some hints regarding the particular features that guide control in the Stroop task. The item-specific proportion congruence effect was observed in the multiple- and single-feature conditions. Both included an item-specific proportion congruence manipulation that varied proportion congruence for particular color-word pairs. This suggests that participants used word information to guide responses. Given the equivalence in the magnitude of the item-specific proportion congruence effect between conditions, it appears that participants in the multiple-features condition did not take advantage of the additional feature, font type, which was also correlated with proportion congruence. This may be because words themselves are highly salient and receive greater attention than do particular perceptual features, such as font type. In this sense, the relationship between particular words and proportion congruence levels may have overshadowed the relationship between particular font types and proportion congruence levels.

Alternatively, this pattern of findings may be related to the underlying mechanisms that reduce susceptibility to Stroop interference when participants respond on the basis of particular words (item-specific manipulation) versus particular word features (font-type manipulation). That is, the words themselves are predictive of the likelihood of congruency (as previously described), and this may lead participants to adopt different word-reading policies for mostly congruent as compared with mostly incongruent words. The words also are associated with particular color responses. For example, when BLUE and YELLOW are mostly congruent, 80% of the time BLUE appears in blue ink and YELLOW appears in yellow. In contrast, BLUE appears rarely in yellow and YELLOW appears rarely in blue. The opposite is true for mostly incongruent items. As suggested by Jacoby et al. (2003), attending to and responding on the basis of the word can lead to fast and accurate production of the correct response on 80% of the trials (for similar accounts, see Melara & Algom, 2003; Musen & Squire, 1993; Schmidt & Besner, 2008; Schmidt, Crump, Cheesman, & Besner, 2007).

Font type, too, predicts the congruency of particular word pairs; therefore, participants may respond differentially to words printed in a mostly congruent relative to a mostly incongruent font type, on the basis of unique word-reading policies that have been established for each font type. In this sense, responding on the basis of item- or font-specific control may represent the action of a similar control mechanism. Unlike the word information that signals item-specific proportion congruence, however, font type does not predict specific responses and therefore does not permit responding on the basis of simple associations. In the present experiment, then, reliance on the word and on the information it carried regarding both the likelihood of congruency and the specific response to produce may have been a sufficiently efficient means of buffering Stroop interference such that other available features (e.g., font type) were not exploited in an effort to implement control over word reading. That is, font type, and the information it carried regarding the likelihood of congruence, may not have offered any additional advantages to performance that the word information alone did not offer already.

This result raises the question of whether font type, if it were the only feature correlated with proportion congruence, would produce a proportion congruence effect. That is, is there a control mechanism that can modulate word reading differentially for mostly congruent and incongruent items when proportion congruence is manipulated at the level of font type rather than at the level of the word itself? Experiment 3 addressed this question.

EXPERIMENT 3

Incongruent and congruent stimuli were presented equally often in two distinguishable font types. For one font type, items were mostly congruent; for the other, items were mostly incongruent. Stimuli appearing in each font type were presented equally often in the four colors used in the present experiment. As such, font type could not be used to predict specific responses. If font type, due to its ability to predict congruency, is used to control word reading, then Stroop interference should be smaller for items appearing in the mostly incongruent relative to the mostly congruent font type.

Method

Participants. Twenty-two Washington University students participated in partial fulfillment of course credit or in exchange for monetary compensation. All participants were native English speakers, with normal color vision and with normal or corrected-to-normal visual acuity.

Design and Materials. At the list level, an equal number of congruent and incongruent stimuli were randomly presented along with eight neutral (%%%%%) items. Each of the four stimulus words (BLUE, GREEN, WHITE, and YELLOW) was presented 50% of the time in the congruent color and 50% of the time in an incongruent color (~33% of the time in each of the three incongruent colors). Bookman Old Style font was used to compose half of the trials; Arial was used in the other. Items presented in one of the two font types were mostly congruent (~80%), and items presented in the other font type were mostly incongruent (~80%). The assignment of font type to proportion congruence was counterbalanced across participants. All four stimulus words and colors appeared equally often in the mostly congruent and mostly incongruent font types.

Procedure. The procedure was identical to that in Experiment 1, with a few exceptions. Participants completed 20 practice trials (8 in Arial font type and 8 in Bookman Old Style that each included all possible word/color combinations and preserved the font-specific proportion congruence of the test blocks, and 4 neutral trials) prior to completing two blocks of 120 test trials.

Results

For each participant, RTs less than 200 msec and greater than 3,000 msec were removed, which eliminated fewer than 1% of the trials. Overall, errors were low (1.4%). There were no significant effects in the analysis of error rates other than the finding that more errors were made on incongruent ($M = 2.4\%$) versus congruent ($M = 0.4\%$) trials [$F(1,21) = 18.69$, $MS_e = .00$, $p < .01$]. Therefore, to conserve space, we report only the analysis of correct RTs.

A 2×2 within-subjects ANOVA was conducted with proportion congruence (mostly congruent vs. mostly incongruent) and trial type (congruent vs. incongruent) as factors. Incongruent trials ($M = 738$) were responded to more slowly than congruent trials ($M = 632$) [$F(1,21) = 103.34$, $MS_e = 2{,}398$]. As indicated by the proportion congruence $\times$ trial type interaction, the magnitude of Stroop interference was smaller for the mostly incongruent ($M = 96$) than for the mostly congruent ($M = 116$) font type [$F(1,21) = 4.78$, $MS_e = 4.78$, $p < .05$]. Given that this is the first report in the literature of a font-specific proportion congruence effect of which we are aware, we subsequently analyzed the proportion congruence $\times$ trial type interaction for each block of the task to characterize the time course of the effect. Our reasoning was that the association between font type and proportion congruence might develop slowly, such that the reliability of this interaction may be limited to performance in the second block. The analyses confirmed that this was the case. In Block 2, Stroop interference was smaller for items that appeared in the mostly incongruent font type ($M = 94$) than for those that appeared in the mostly congruent font type ($M = 121$) [$F(1,21) = 4.60$, $MS_e = 886$, $p < .05$]. Although a similar pattern was observed in Block 1, with interference being smaller for items appearing in the mostly incongruent ($M = 99$) relative to the mostly congruent ($M = 110$) font type, the interaction was less marked and not statistically reliable ($F < 1$).

Discussion

The observation of a font-specific proportion congruence effect implies that word reading can be modulated differentially for mostly congruent and incongruent items when congruency is signaled by a particular font type. Broadly speaking, this finding suggests that control over word reading in the Stroop task can be exerted at the font level in addition to the item level and list level.[3]

Font-level control over Stroop interference may be accomplished by a mechanism that, upon onset of the Stroop stimulus, rapidly extracts predictive perceptual features, such as the font type itself or the shape of the word as written in a particular font type, and uses such features to differentially modulate word reading. A more refined hypothesis is that font type is used as an early signal for controlling a word-reading *filter* (Jacoby et al., 2003; Jacoby, McElree, & Trainham, 1999). The idea here is that the word itself would be filtered more quickly for words appearing in the mostly incongruent relative to the mostly congruent font, such that further processing of the word beyond its low-level perceptual features may be inhibited. Importantly, a similar control mechanism might also underlie the item-specific proportion congruence effect observed previously (Jacoby et al., 2003), although the action of this mechanism may be driven by features of the stimulus different from those that produce the font-specific proportion congruence effect. For instance, one might learn that particular words that are longer or shorter tend to come from a mostly incongruent word pair and use this information to filter word reading. This remains to be tested.

The font-specific proportion congruence effect is perhaps part of a larger class of context-specific proportion congruence effects. The term *context-specific proportion congruence effect* was coined by Crump, Gong, and Milliken (2006), who showed that the magnitude of Stroop interference was significantly smaller when stimuli appeared in a mostly incongruent relative to a mostly congruent location. As with the font-specific proportion congruence effect, the context-specific proportion congruence effect cannot be accounted for by a simple contingency (e.g., stimulus–response learning) account, because the contextual cue (i.e., location) was associated equally often with all possible responses, just as font type was in the present experiment. Admittedly, a more complex contingency account based on compound font type–word–response associations might at least partially account for the font-specific proportion congruence effect and, similarly, the context-specific proportion congruence effect.

An important difference between the font-specific proportion congruence effect and the context-specific proportion congruence effect relates to the different Stroop paradigms that were used to evaluate these effects. Crump et al. (2006, Experiment 2A) used a priming procedure whereby a color-word prime was presented briefly in black ink and was followed by a display featuring a colored rectangle that appeared above or below fixation in either the mostly congruent or the mostly incongruent location. The participants' task was to name the color of the rectangle. Crump et al. speculated that the relevant contextual cue (i.e., location) might be modulating the degree to which the prime word is integrated with the color of the rectangle in the probe display, thus impacting Stroop interference. This control mechanism is very different from the notion of a word-reading filter that may be modulating word reading and producing the font-specific proportion congruence effect in our paradigm. A strong appeal of the latter mechanism is that a word-reading filter might explain Stroop interference effects more broadly, as in other common paradigms involving integrated color/word stimuli.

GENERAL DISCUSSION

Human behavior is incredibly flexible. In some contexts, stimulus–response associations that are acquired via repeated experience are used to guide responding. Novel or unpredictable contexts, however, often necessitate a shift toward responding on the basis of higher level goals or expectations that may change on a moment-to-moment basis. The present analysis suggests that there are multiple approaches to controlling behavior and that such approaches are bound by contextual features. Similarly, the experiments presented here suggest that there are multiple levels at which one can exert control over Stroop interference and that engagement of these levels is triggered differentially for differing contexts.

In the present study, both younger and older adults demonstrated use of item-specific control, which involves the use of word information rapidly upon stimulus onset to modulate the influence of the word-reading process on Stroop performance (Jacoby et al., 2003). When pairs of words (i.e., items) are mostly incongruent, Stroop effects are significantly smaller than when pairs of words are mostly congruent. As first outlined by Jacoby et al. (2003), at least two mechanisms may underlie item-level control: a cognitive-control mechanism and an associative-learning mechanism. The cognitive control mechanism purportedly involves stronger dampening of the word-reading process upon stimulus onset particularly in the case of items from a mostly incongruent word pair (see also Jacoby, McElree, & Trainham, 1999). In contrast, the associative-learning mechanism involves the production of the color response that is associated most frequently with a particular word. For example, for a mostly incongruent word pair (e.g., BLUE and YELLOW), a participant would quickly produce the response "yellow" when presented with the word BLUE because most of the time this is the correct response. However, when the most frequent response is the incorrect response, as in the case of incongruent trials in a mostly congruent condition, reliance on this associative mechanism can create inflated error rates due to response prediction error, which was observed for younger adults in the mostly congruent condition in Experiment 1. Although the present results do not allow us to adjudicate fully between a control account and an associative learning account, it is important to acknowledge that item-level control can be achieved through either or both of these mechanisms.

In the present study, we also observed font-level control, which to our knowledge is a level of control not previously explored. The initial observation of a font-specific proportion congruence effect occurred in Experiment 3. In this experiment, items that were printed in a particular font type were mostly congruent, whereas items printed in a second font type were mostly incongruent. Stroop effects were significantly smaller for items printed in the mostly incongruent font type. The font-specific proportion congruence effect, like the item-specific proportion congruence effect, must reflect a mechanism that acts after stimulus onset, because 50% of the stimuli within a block of trials appear in the mostly congruent font and 50% appear in the mostly incongruent font. These proportions prohibit participants from anticipating the type of font that will occur on the upcoming trial and adjusting control settings prior to stimulus onset.

In the case of item-specific or font-level control, the particular operations that are engaged immediately after stimulus onset remain to be fully explicated. One possibility is that the two levels of control, at least in part, reflect the action of a single control mechanism that is "turned on" by different features of the stimulus. Participants may detect features (e.g., entire words, in the case of item-specific control, or distinctive font types or shapes, in the case of font-specific control) that are predictive of proportion congruence levels and use control mechanisms to gate word-reading processes accordingly. For example, item-specific and/or font-level control may involve processes that modulate word reading on the basis of the degree of interference (i.e., response conflict) each stimulus produces post-stimulus onset. Particular stimuli (or features of stimuli) that are associated with a high probability of incongruence may lead to greater conflict at onset and relatively stronger gating of word reading. Indeed, if item-specific or font-level control act after the detection of conflict, one might anticipate sequential adjustments in the form of conflict adaptation (see, e.g., Botvinick et al., 2001) in paradigms where these control processes are operating. Although the present findings and those using process dissociation (e.g., Jacoby et al., 2003; Lindsay & Jacoby, 1994) anticipate such adjustments to follow the form of weight changes in the reading pathway, changes might take place in the color pathway instead, as evidenced in the item-specific conflict-monitoring model (Blais et al., 2007).

Alternatively, item-specific and/or font-level control may be acting post-stimulus onset, but prior to the occurrence of interference or conflict. For instance, detection of critical features such as font type may be accompanied by rapid gating of word-reading processes before response conflict arises, particularly in the case of incongruent trials from a mostly incongruent condition. Similarly, in the case of item-specific responding on the basis of learned associations, presentation of the stimulus (word) may lead to rapid retrieval of the associated response prior to the occurrence of conflict. According to this view, item-specific and/or font-level control may involve "early selection" processes (Jacoby, Kelley, & McElree, 1999). These processes should not, however, be equated with the proactive control processes described in the context of the dual mechanisms of control account (Braver et al., 2007). This account conceptualizes proactive control processes as acting prior to stimulus onset, whereas the proposed mechanisms just described may be acting post-stimulus onset.

A third level of control, which operates at the list level, is the most pervasive control mechanism identified in the extant literature regarding proportion congruence effects in Stroop paradigms (e.g., Logan & Zbrodoff, 1979; Logan et al., 1984). Unlike the item-specific and font levels of control, list-level control is purported to involve proactive global strategies, operating prior to stimulus onset. List-level strategies largely reflect expectations. For example, in mostly incongruent lists, incongruent items are expected. To reduce Stroop interference in such a context, participants are believed to use a consistent trial-to-trial strategy that involves adjusting cognitive control settings away from word reading and toward color naming. In the present study, we did not, however, find evidence of list-level control. In fact, the results of Experiment 1 raise the question of whether prior observations of list-wide proportion congruence effects may reflect item-level control, at least partially and perhaps fully.

Across three experiments, then, we have uncovered two levels of control (item level and font level) that were implemented in service of reducing Stroop interference. The second key question we addressed is whether participants would simultaneously exploit more than one level of control. Experiments 1 and 2 were informative on this issue. Neither showed clear evidence of the simultaneous implementation of two control levels. There are several potential reasons for this finding.

Above, we described both the item-level and font-level mechanisms as being more flexible in nature, rapidly adjusting control settings after stimulus onset on a word-by-word or trial-by-trial basis. If this is the case, one reason that item- and font-level control may *not* operate simultaneously in contexts that allow for control to be implemented at both levels, as in Experiment 2, is that the two levels of control may be redundant. That is, using both levels simultaneously may not produce reductions in interference proportional to the additional effort that may be required to do so. Alternatively, item- and font-level control may interfere with one another. For instance, if participants divide attention between the two dimensions (word and font type), performance may suffer as compared with when they choose a single dimension and respond accordingly. Of course, both of these explanations assume that the font type manipulation in Experiment 2 was sufficiently salient for participants to have the option of using item- and font-level control simultaneously.

Although a redundancy, interference, or saliency explanation may suffice in explaining why multiple levels of control were not operative when the available levels were item level and font level, these explanations do not fare well in explaining the results of Experiment 1, wherein only an item-level effect was observed even though a list-wide proportion-congruence manipulation was also implemented. An account based on the mechanisms that underlie each level of control is elaborated next in an attempt to explain the patterns observed across Experiments 1 and 2. In these experiments, participants may have elected to attend to the item-specific proportion congruence manipulation that occurred at the level of words, rather than the list-wide or font-type proportion congruence manipulation, because item-level control afforded participants the opportunity to respond to each word on the basis of stimulus–response associations. This type of responding may eliminate the need for engagement in effortful modification of control settings, because stimulus–response associations may be retrieved prior to the occurrence of interference or conflict on incongruent trials. Other levels of control may have little value in such a context. Two predictions follow from this account. The first is that increased use of list-wide or font-specific levels of control should occur to the extent that one reduces the efficiency of item-level control. Second, if two levels of control (e.g., list level and font level) were available in a single task context and neither level permitted responding on the basis of simple stimulus–response learning, one might observe the simultaneous implementation of both levels of control. These predictions remain to be tested.

Conclusion

The present set of experiments indicates that multiple levels of control are used in service of control over Stroop interference. An item level of control surfaced in task contexts in which other levels of control were available but were not used. A second level of control, the font level, was revealed for the first time in the present study. Although a third level of control, list-wide, has been observed in prior reports, we did not observe it here when any item-specific influence that could contribute to its observation was controlled. This finding suggests caution in interpreting list-wide proportion congruence effects in Stroop tasks as reflecting solely strategic or global forms of control. Rather, our findings indicate that an account of proportion congruence effects in Stroop experiments must consider multiple levels of control that are used to modulate Stroop interference and that these levels can operate differentially from trial to trial.

AUTHOR NOTE

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REFERENCES

BLAIS, C., ROBIDOUX, S., RISKO, E. F., & BESNER, D. (2007). Item-specific adaptation and the conflict-monitoring hypothesis: A computational model. *Psychological Review*, **114**, 1076-1086.

BOTVINICK, M. M., BRAVER, T. S., BARCH, D. M., CARTER, C. S., & COHEN, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, **108**, 624-652.

BRAVER, T. S., GRAY, J. R., & BURGESS, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 76-106). New York: Oxford University Press.

BRINK, J. M., & MCDOWD, J. M. (1999). Aging and selective attention: An issue of complexity or multiple mechanisms? *Journals of Gerontology*, **54B**, P30-P33.

CARTER, C. S., MACDONALD, A. M., BOTVINICK, M., ROSS, L. L., STENGER, V. A., NOLL, D., & COHEN, J. D. (2000). Parsing executive processes: Strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences*, **97**, 1944-1948.

COHEN, J. D., DUNBAR, K., & MCCLELLAND, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, **97**, 332-361.

CRUMP, M. J. C., GONG, Z., & MILLIKEN, B. (2006). The context-specific proportion congruent Stroop effect: Location as a contextual cue. *Psychonomic Bulletin & Review*, **13**, 316-321.

DE JONG, R., BERENDSEN, E., & COOLS, R. (1999). Goal neglect and inhibitory limitations: Dissociable causes of interference effects in conflict situations. *Acta Psychologica*, **101**, 379-394.

JACOBY, L. L. (1991). A process dissociation framework: Separating automatic from intentional uses of memory. *Journal of Memory & Language*, **30**, 513-541.

JACOBY, L. L., KELLEY, C. M., & MCELREE, B. D. (1999). The role of cognitive control: Early selection versus late correction. In S. Chaiken & Y. Trope (Eds.), *Dual-process theories in social psychology* (pp. 383-400). New York: Guilford.

JACOBY, L. L., LINDSAY, D. S., & HESSELS, S. (2003). Item-specific control of automatic processes: Stroop process dissociations. *Psychonomic Bulletin & Review*, **10**, 638-644.

JACOBY, L. L., MCELREE, B. [D.], & TRAINHAM, T. N. (1999). Automatic influences as accessibility bias in memory and Stroop tasks: Toward a formal model. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII: Cognitive regulation of performance. Interaction of theory and application* (pp. 461-486). Cambridge, MA: MIT Press.

LINDSAY, D. S., & JACOBY, L. L. (1994). Stroop process dissociations: The relationship between facilitation and interference. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 219-234.

LOGAN, G. D., & ZBRODOFF, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*, **7**, 166-174.

LOGAN, G. D., ZBRODOFF, N. J., & WILLIAMSON, J. (1984). Strategies in the color-word Stroop task. *Bulletin of the Psychonomic Society*, **22**, 135-138.

LOWE, D. G., & MITTERER, J. O. (1982). Selective and divided attention in a Stroop task. *Canadian Journal of Psychology*, **36**, 684-700.

MACLEOD, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, **109**, 163-203.

MELARA, R. D., & ALGOM, D. (2003). Driven by information: A tectonic theory of Stroop effects. *Psychological Review*, **110**, 422-471.

MUSEN, G., & SQUIRE, L. R. (1993). Implicit learning of color–word associations using a Stroop paradigm. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **19**, 789-798.

MUTTER, S. A., NAYLOR, J. C., & PATTERSON, E. R. (2005). The effects of age and task context on Stroop task performance. *Memory & Cognition*, **33**, 514-530.

SCHMIDT, J. R., & BESNER, D. (2008). The Stroop effect: Why proportion congruent has nothing to do with congruency and everything to do with contingency. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **34**, 514-523.

SCHMIDT, J. R., CRUMP, M. J. C., CHEESMAN, J., & BESNER, D. (2007). Contingency learning without awareness: Evidence for implicit control. *Consciousness & Cognition*, **16**, 421-435.

SHOR, R. E. (1975). An auditory analog of the Stroop test. *Journal of General Psychology*, **93**, 281-288.

SPIELER, D. H., BALOTA, D. A., & FAUST, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 461-479.

STROOP, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, **18**, 643-662.

TOTH, J. P., & JACOBY, L. L. (2003, November). *Effects of age and list-wide versus item-specific proportion congruency in the Stroop task.* Poster presented at the 44th Annual Meeting of the Psychonomic Society, Vancouver, BC.

TZELGOV, J., HENIK, A., & BERGER, J. (1992). Controlling Stroop effects by manipulating expectations for color words. *Memory & Cognition*, **20**, 727-735.

VERHAEGHEN, P., & DE MEERSMAN, L. (1998). Aging and the Stroop effect: A meta-analysis. *Psychology & Aging*, **13**, 120-126.

WEST, R., & BAYLIS, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology & Aging*, **13**, 206-217.

NOTES

1. This explanation was elaborated and tested initially in a poster presented by Toth and Jacoby (2003) at the 44th Annual Meeting of the Psychonomic Society in Vancouver, BC.

2. Analysis of the log-transformed RTs indicated that older adults showed larger Stroop interference effects than did younger adults on both the item-specific PC-50 trials [$F(1,68) = 8.11$, $MS_e = .001$] and the item-specific PC-25 and PC-75 trials [$F(1,68) = 10.92$, $MS_e = .001$]. List-wide proportion congruence had no influence on the magnitude of the Stroop effect ($F < 1$), whereas item-specific proportion congruence had large effects on this measure [$F(1,68) = 38.84$, $MS_e = .001$]. Most critically, the age × proportion congruence × trial type interactions were nonsignificant for the list-wide and item-specific analyses (Fs < 1), indicating that the list-wide and item-specific manipulations had a similar effect on the magnitude of Stroop interference for younger and older adults. In fact, the increase in Stroop interference from the item-specific PC-25 to the item-specific PC-75 condition was almost identical for older ($M = .06$) and younger ($M = .05$) adults.

3. List-level control was not observed in Experiment 1 in the present study; however, this is not to say that list-wide control will never emerge in Stroop paradigms. List-wide control may be used, for instance, in task contexts that do not afford item-specific control.

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