Psychonomic Bulletin & Review
2003, 10 (3), 638-644

Item-specific control of automatic processes: Stroop process dissociations

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The influence of word reading on Stroop color naming decreases as a function of the proportion of test items that are incongruent. This proportion-congruent effect is usually ascribed to strategies (e.g., maintaining task set) that operate at a general level to moderate the extent to which participants are influenced by word reading. However, in three experiments, effects at the level of specific items were found. Interference and facilitation were smaller for color names usually presented in an incongruent color than for color names usually presented in their congruent colors. This item-specific proportion-congruent manipulation affected the process dissociation (PD) estimate of the influence of word-reading processes but not that of color-naming processes. The results (1) indicate that item-specific, as opposed to general, mechanisms can reduce the influence of word-reading processes on Stroop performance and (2) demonstrate the PD procedure's utility in studying Stroop phenomena.

In the Stroop (1935) task, participants are to identify the colors in which color words and control stimuli are visually displayed (for a review, see MacLeod, 1991). Performance on this task is influenced by word-reading processes as well as by the intended color-naming processes, as revealed by Stroop interference (i.e., slower correct color-naming responses on incongruent items than on, for example, a string of green ampersands). Stroop interference is affected by the proportion of congruent (i.e., the word RED in red ink) versus incongruent (i.e., the word RED in green ink) items: The higher the proportion of incongruent items, the less interference there will be (see, e.g., Lindsay & Jacoby, 1994; Logan, 1980; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982; Shor, 1975; Tzelgov, Henik, & Berger, 1992).

Differential effects of proportion congruence on the magnitude of Stroop interference have been interpreted as evidence that goal maintenance is a critical factor in performing the Stroop task (see, e.g., West, 1999). Increasing the proportion of items that are incongruent increases the importance of maintaining the goal of color naming so as to avoid interference produced by word reading. Moreover, the ability to maintain the goal of color naming is thought to vary across individuals (see, e.g., Kane & Engle, 2002; West & Baylis, 1998). For example, older adults are said to be less able to reliably maintain the color-naming goal and, so, show an age-relative increase in Stroop interference when items are mostly incongruent (MI; West & Baylis, 1998). This goal-maintenance perspective is related to Duncan's work on "goal neglect" (Duncan, 1990, 1993, 1995; for similar views, see De Jong, Berendson, & Cools, 1999; Roberts & Pennington, 1996). Duncan argues that goal maintenance has its effect by means of an attentional, goal-weighting process that relies on intact prefrontal cortex function. The model of Stroop phenomena proposed by Cohen, Dunbar, and McClelland (1990) includes a central, task-demand mechanism that keeps participants on task (i.e., naming colors rather than naming words). By their model, task demand nodes modulate the extent to which processing occurs along a word-naming path versus a color-naming path.

Differences in a central, task demand mechanism that supports goal maintenance can be used to account for a general effect of proportion congruent on word reading that operates at a list-wide level. An objective of the present research was to further show that item-specific mechanisms as well as general mechanisms can modulate the influence of word-reading processes. Findings of item-specific effects suggest the possibility of multiple levels of control of automatic processes in performance of Stroop tasks. To show item-specific effects, an experiment by Ja-

This research was supported by research grants from the Natural Science and Engineering Research Council of Canada to L.L.J. and D.S.L. and by National Institute on Aging Grant AG13845 to L.L.J. Special thanks to Ann Hollingshead of McMaster University for her contribution of both research support and data collection. Correspondence concerning this article should be addressed to L. L. Jacoby, Department of Psychology, Box 1125, One Brookings Dr., Washington University, St. Louis, MO 63130-4899 (e-mail: lljacoby@artsci.wustl.edu).

coby (Jacoby, McElree, & Trainham, 1999; Trainham, Lindsay, & Jacoby, 1997) varied proportion congruence at the level of items by making two binary pairs of four colors. For one binary pair (e.g., blue and yellow), trials were congruent 80% of the time, whereas for the other binary pair (e.g., white and green), trials were congruent 20% of the time. Each color name appeared in its own color for congruent items and in the color of the other member of its pair for incongruent items. The overall proportion congruence was 50% at the list-wide level. The results revealed an effect of item-specific proportion congruence (ISPC) that is the same as what is found when proportion congruence is manipulated at a list-wide level. That is, the magnitude of Stroop interference was smaller for words that were MI than for words that were mostly congruent (MC).

The ISPC effect cannot be accounted for by appealing to differential reliance on a central task-demand mechanism (see, e.g., Cohen et al., 1990; West & Baylis, 1998). Participants cannot weight color-naming processes more heavily in expectation of an MI item, because they never know what kind of item will be presented from one trial to another. Stated differently, participants must identify a word as being one that is MI with its color before weighting color-naming processes more heavily—effects of ISPC cannot be accounted for by differential maintenance of task goals at a general, situation-wide level. Experiments 1 and 2 replicated and extended our prior findings of an effect of ISPC. In Experiment 3, we examined the rate at which the ISPC effect develops.

A second aim of the present experiments was to further assess the usefulness of Jacoby's (1991) process dissociation (PD) procedure as a means of separately estimating the contributions of word-reading and color-naming processes to performance on the Stroop task (Jacoby et al., 1999; Lindsay & Jacoby, 1994; Trainham et al., 1997). To apply the PD procedure to Stroop task performance, Lindsay and Jacoby (1994) used a response deadline and scored performance in terms of accuracy rather than latency. Correct color-naming responses made within deadline were scored as correct, and errors made within deadline and failures to respond within deadline were scored as incorrect.

Under the independence assumption, the probability of correct naming of the color of congruent items within deadline is $p(\text{correct}\,|\,\text{congruent}) = \text{word} + \text{color}(1 - \text{word})$. That is, participants will correctly name the color of congruent items within the deadline to the extent that word-reading processes and/or color-naming processes sufficiently influence the response within that time. The probability of naming the color of incongruent items within deadline is assumed to be $p(\text{correct}\,|\,\text{incongruent}) = \text{color}(1 - \text{word})$. That is, participants will correctly name the color of an incongruent item within the time limit only to the extent that color-naming processes, and not word-reading processes, sufficiently influence the response within the deadline. With this equation, it is assumed that the rapid, highly practiced word-reading processes dominate over color-naming processes.

Subtracting the equation for incongruent items from that for congruent items yields an estimate of the influence of word-reading processes (W). Using that estimate, an estimate of the influence of color-naming processes (C) can be algebraically derived using either equation.

A PD is obtained when an experimental manipulation that should, on theoretical grounds, selectively affect one of the component processes does indeed affect the appropriate parameter estimate and not the other. Such findings support the hypothesis that the two kinds of processes are independent, as the equations assume. Lindsay and Jacoby (1994) showed that manipulating the discriminability of the colors in a Stroop task substantially affected the estimate of C but had no effect on the estimate of W, and that manipulating the proportion of congruent items dramatically altered the estimate of W but left the estimate of C invariant. Converging evidence of the approach came from the finding that the estimate of C (derived from performance on congruent and incongruent words) predicted performance on nonletter control items. Jacoby et al. (1999; also see Trainham et al., 1997) developed the PD Stroop counter model to illustrate a way in which the independence and dominance assumptions of the PD approach can be instantiated in a processing model that can account for Stroop effects measured in terms of response latency as well as in terms of accuracy within response deadline.

Returning to questions about level(s) of control in performance of Stroop tasks, we used the PD procedure to replicate our earlier finding that manipulating proportion congruent at the item-specific level produces effects that are the same as those produced when proportion congruent is manipulated at the list-wide level. On the basis of what was found in the earlier experiment, we expected the manipulation of ISPC to selectively influence the contribution of word-reading processing independently of the contribution of color-naming processing. Experiment 1 differed from the earlier experiment in that triplets rather than pairs of colors were used to implement the manipulation of ISPC. For incongruent trials, this change results in the appearance of a color with two incongruent color words, rather than with a single, incongruent color word.

EXPERIMENT 1

Method

Participants. The participants were 14 students from an introductory psychology course at McMaster University who voluntarily participated for course credit. All the participants were native speakers of English with normal color vision and normal or corrected-to-normal visual acuity.

Materials and Procedure. Six colors and their corresponding color words were chosen and divided into two sets (red, yellow, and white vs. black, blue, and green). Each color word was presented 50 times in the experiment: Words from one set were presented in their congruent colors on 40 trials (80%) and in another color from that set on the remaining 10 trials (20%; 10% for each incongruent color) to produce MC items. For words from the other color set, these rates were reversed to produce MI items. Assignment of color sets to the MI and MC conditions was counterbalanced across participants. There were also 4 control trials of each color, 2 with a string of five percent signs (%%%%%) and 2 with a string of six percent signs

(%%%%%%). Thus, over the experiment, there were 150 congruent trials, 150 incongruent trials, and 24 control trials, with each color and each color-name word appearing equally often.

The test list of 324 items was divided into two blocks of 162 items each. Each block was completely balanced according to the 80%–20% manipulation. Item order was fixed for all the participants and was random except for the constraint that no more than 3 congruent or 3 incongruent items were presented in succession. Presentation of the test list was preceded by a 25-item practice list. The representation of conditions by items in this practice list was approximately the same as in the test list. There was no break between the practice phase and the test list; however, during the practice trials (but not the test trials) the participant's response time on each item appeared on the lower right-hand side of the screen. After the practice phase and the first half of the test list, there was a break for a minute or two for the participants to rest their eyes, and then the second half of the test list was presented.

The experiment was conducted using a PC. The participants were told that items would appear one at a time on the screen against a gray background and that their task was to name the color in which each item was printed. They were told that they would have 550 msec in which to respond and that if they did not respond prior to the deadline, the screen would flash black. Each item remained on the screen for a maximum of 550 msec. If the participant responded within the deadline, the screen cleared; if not, the screen flashed black and then returned to gray. After a delay of 1 sec, the next trial was presented.

Results

The probabilities of a correct response (correct color name said within 550 msec) are shown in Table 1 for congruent, incongruent, and control items. An omnibus analysis of variance (ANOVA) indicated no main effect or interactions involving block, so the analyses we report collapsed across that factor. The congruence × proportion congruent interaction was significant, the difference in accuracy between congruent and incongruent items being greater in the MC than the MI condition [$F(2,26) = 10.62$, $MS_e = 0.0080$, $p < .001$].

The mean estimates of W and C are presented in Table 2. A one-way ANOVA revealed that W was significantly higher in the MC than in the MI condition [$F(1,13) = 20.76$, $MS_e = 0.013$, $p < .005$]. In contrast, the estimates of C were nearly equivalent in the MI and MC conditions ($F < 1$). The correlation between C and proportion correct on control items was $r(12) = .757$ ($p < .01$). These findings replicate those of Jacoby et al. (1999) and converge with the Lindsay and Jacoby (1994) experiments, in which proportion congruent was manipulated at the general, list-wide level.

Table 1
Experiment 1: Mean Proportion Correct Color Naming Within 550 Msec, With Standard Deviations (*SDs*)

	Item Type					
	Congruent		Incongruent		Control	
Proportion Congruent	*M*	*SD*	*M*	*SD*	*M*	*SD*
Mostly congruent	.87	.10	.24	.22	.69	.26
Mostly incongruent	.79	.16	.36	.23	.61	.26

Table 2
Experiment 1: Mean Estimates of W and C, With Standard Deviations (*SDs*)

	Parameter			
	W		C	
Proportion Congruent	*M*	*SD*	*M*	*SD*
Mostly congruent	.63	.20	.60	.28
Mostly incongruent	.43	.25	.61	.24

EXPERIMENTS 2A AND 2B

Experiments 2A and 2B conceptually replicated Experiment 1, with two important additional features. First, in addition to a block in which some color-name words were usually in the congruent condition and others were usually in the incongruent condition, the participants also completed a block in which each color name was equally often congruent and incongruent with the color in which it appeared. Second, there were two versions of the experiment: Experiment 2A was a standard Stroop task, with data analyzed in terms of response latency, whereas in Experiment 2B a response deadline was used and data were analyzed in terms of proportion correct and estimates of W and C.

Method

Participants. The participants were 32 students from an introductory psychology course at the University of Texas at Austin, who voluntarily participated for course credit. Half of the participants were assigned to Experiment 2A and half to Experiment 2B. All were native speakers of English and reported having normal color vision and normal or corrected-to-normal visual acuity.

Materials and Procedure. Four colors were chosen and divided into two sets (green and white vs. blue and yellow) to produce MC and MI items. The probability of a color word's being congruent with the color in which it appeared was .75 for MC items (36 of 48 presentations) and .25 for MI items (12 of 48 presentations). In a second list, both sets of color-name words were presented in their congruent colors half of the time and in the incongruent color half of the time. In each of the two lists, each color was presented as a control item on 6 trials, 3 with five percent signs and 3 with six percent signs. Thus, there were a total of 216 trials in each list. A practice phase consisting of 18 items was presented at the beginning of the experiment. List order was counterbalanced across participants. Other details were the same as in Experiment 1. Experiments 2A and 2B differed only in deadline for responding; the deadlines were 3,000 msec and 550 msec, respectively.

Results

Experiment 2A. Response accuracy was high for all conditions ($M = .99$). The mean median response times for correct responses for congruent, incongruent, and control items are shown in Table 3. There was a significant item type × proportion congruent interaction [$F(4,60) = 3.96$, $p < .005$], with the difference in response latency between congruent and incongruent items decreasing with proportion incongruent (mean differences of 112 msec, 91 msec, and 61 msec in the MC, 50/50, and MI conditions, respectively).

Table 3
Experiment 2A: Mean Median Correct Color-Naming Response Latencies (in Milliseconds), With Standard Deviations (*SD*s)

	Item Type					
	Congruent		Incongruent		Control	
Proportion Congruent	*M*	*SD*	*M*	*SD*	*M*	*SD*
Mostly congruent	569	51	681	85	609	64
50/50	590	61	681	77	636	44
Mostly incongruent	588	79	649	78	591	43

We used post hoc deadlines to compute PD estimates of W and C for MC and MI items (Figure 1). Mean proportions correct on congruent and incongruent items in the MC and MI conditions were calculated at 50-msec intervals between 600 and 750 msec, and those means were used to estimate C and W at each deadline. As was expected, C increased across post hoc deadlines, whereas W decreased. Moreover, at each of the post hoc deadlines, W was higher for MC than for MI items, whereas C was invariant for the two item types. The changes in C and W across post hoc deadlines converge with the results reported by Lindsay and Jacoby (1994). They reported a dissociation opposite to that reported here by showing that discriminability of colors influenced C but left W invariant at each post hoc deadline.

Experiment 2B. The proportions of responses scored as accurate (correct color name said within 550 msec) for congruent, incongruent, and control items are presented in Table 4. Differences between accuracy for congruent and incongruent items varied with proportion congruent, yielding a significant item type × proportion congruent interaction [$F(4,60) = 4.55$, $MS_e = 0.010$, $p < .005$].

The mean estimates of W and C are presented in Table 5. A one-way repeated measures ANOVA revealed a reliable effect of proportion congruent on W [$F(1,15) = 18.25$, $MS_e = 0.016$, $p < .005$]. The mean estimates of C were not reliably affected by proportion congruent [$F(1,15) = 2.51$, $MS_e = 0.006$]. The correlation between C and proportion correct on control items was $r(14) = .76$ ($p < .01$).

The pattern of effects obtained in Experiment 2B using a response deadline and measuring performance in terms of accuracy was identical to that obtained in Experiment 2A, in which the standard response latency measure was used. The results of both experiments converged with earlier findings in demonstrating an ISPC effect on Stroop interference and on estimates of W, with no effect of the ISPC manipulation on estimates of C.

EXPERIMENT 3

Experiment 3 was designed to explore the time course of the acquisition of the ISPC effect. To that end, test trials were divided into 10 small blocks (not apparent to the participants), and data were analyzed by block.

Method

Participants. The participants were 62 undergraduates at the University of Victoria who voluntarily participated for course credit. All the participants had good English skills and reported that they had normal color vision and normal or corrected-to-normal visual acuity.

Materials and Procedure. Four colors were chosen and divided into two sets (green and white vs. blue and yellow) to construct MC and MI items as in the prior experiments. There were no control strings. The participants were instructed to name the color in which the word was presented as quickly and accurately as possible. To reduce error variance (which was important due to the small number of trials per block), each trial timed out and an error tone sounded if the participant did not respond within 1,500 msec (which occurred on only approximately one postpractice trial per participant). There was an initial eight-item block of practice trials (one occurrence of each item, such that each color name appeared once as congruent

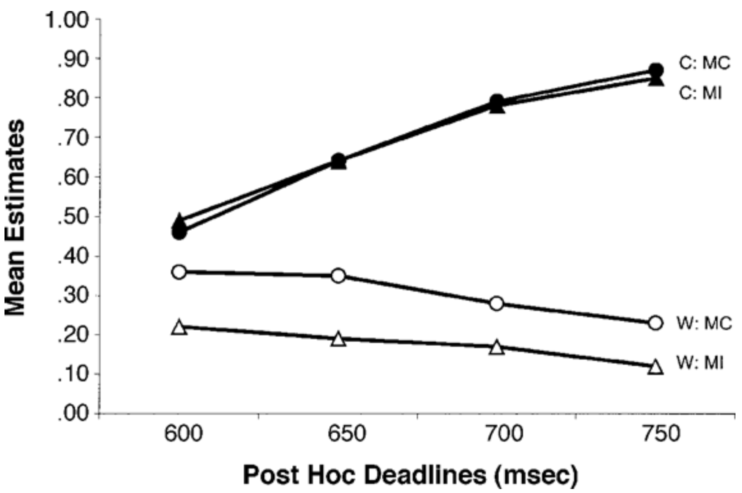

Figure 1. Experiment 2A: Mean estimated contributions of word reading (W) and color naming (C) to performance at each post hoc deadline for mostly congruent (MC) and mostly incongruent (MI) items.

Table 4
Experiment 2B: Mean Proportion Correct Color Naming Within 550 Msec, With Standard Deviations (*SD*s)

	Item Type					
	Congruent		Incongruent		Control	
Proportion Congruent	*M*	*SD*	*M*	*SD*	*M*	*SD*
Mostly congruent	.86	.12	.39	.22	.70	.17
50/50	.82	.14	.45	.22	.68	.20
Mostly incongruent	.77	.13	.50	.22	.75	.17

and once as incongruent); then the instructions were repeated and there was another eight-item block of practice trials (again with no proportion-congruent manipulation) followed immediately by 10 blocks of test trials, each composed of 16 trials (four occurrences of each color name: for one pair of words, three occurrences were congruent and one was incongruent, whereas for the other pair of words, three occurrences were incongruent and one was congruent). There was no pause between blocks.

Results

Accuracy was high for all conditions ($M = .977$), and an analysis of errors revealed no significant effects. Responses were excluded from both latency and accuracy analyses if they were faster than 200 msec (0.24%) or if they exceeded the 1,500-msec maximum (0.62%).

There was a reliable ISPC effect in the latency analyses, in terms of both slower responding to incongruent items in the MC than in the MI condition and faster responding to congruent items in the MC than in the MI condition (Figure 2). For incongruent items, a 2 (ISPC: MC vs. MI) $\times$ 10 (block) within-subjects ANOVA of latency data (with 3 participants dropped due to missing values) revealed a reliable effect of ISPC [$F(1,58) = 21.97$, $MS_e = 17{,}755.22$, $p < .001$]. The linear contrast revealed a nonsignificant tendency of responses to slow slightly across blocks [$F(1,58) = 3.72$, $MS_e = 17{,}506.08$, $p = .059$]. Most interestingly, the block $\times$ ISPC linear interaction did not approach significance ($F < 1$). Visual inspection of Figure 2 suggests that the ISPC effect was greater in Block 2 than in Block 1, but even in an analysis restricted to those two blocks the block $\times$ ISPC interaction was not reliable ($F < 1$). For congruent items, an analogous ANOVA (no participants with missing data) revealed a significant effect of ISPC [$F(1,61) = 14.63$, $MS_e = 3{,}594.65$, $p < .001$] and a reliable linear slowing of responses over blocks [$F(1,61) = 12.37$, $MS_e = 10{,}209.14$, $p < .02$]. Most importantly, the linear contrast for the block $\times$ ISPC contrast was reliable [$F(1,61) = 5.85$, $MS_e = 3{,}022.77$, $p < .02$], showing a small increase in the ISPC effect for congruent items across blocks. In sum, the results indicate that the ISPC effect is very swiftly acquired.

GENERAL DISCUSSION

Our findings extend previous results (Lindsay & Jacoby, 1994; Logan, 1980; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982; Shor, 1975; Tzelgov et al., 1992) in demonstrating that the extent to which automatic word-reading processes influence performance on the Stroop task is dramatically influenced by proportion congruence. Importantly, our results show that such effects can be obtained when proportion congruence is manipulated at an item-specific level. A central task-demand mechanism that modulates word-reading processes at a general level (e.g., Cohen et al., 1990; West, 1999) cannot account for this effect.

Our findings also support the assumptions of the PD procedure, showing the value of jointly considering effects on congruent and incongruent items rather than, for example, emphasizing effects of proportion congruence on Stroop interference alone (Lindsay & Jacoby, 1994). In accordance with the independence assumption, the proportion-congruent manipulation dramatically affected W but had no effect on C (for a discussion of assumptions underlying the application of the PD procedure to Stroop tasks, see Hillstrom & Logan, 1997, and Trainham et al., 1997). Here, we applied the equations at the macro level, across trials, to estimate the influence of W and of C. In the PD Stroop counter model, which describes the dynamics of Stroop processes within trials, the proportion-congruent effect is attributed to variations in the extent to which participants gate or filter input from word-reading processes in response to variations in the proportion of incongruent items (Jacoby et al., 1999; Trainham et al., 1997). Individual differences in goal maintenance can be described as due to effects on the gating mechanism (W) in our PD model.

Perhaps the most interesting question raised by the present experiments concerns the mechanism(s) by which the influence of word-reading processes on Stroop performance is modulated for individual words. One possibility is that an associative mechanism is responsible for the ISPC effect. Pairings of a particular color name with particular colors may lead to associations between color words and responses (Logan, Zbrodoff, & Williamson, 1984; Musen & Squire, 1993). Toth et al. (1995) used the PD procedure to provide evidence that an associative mechanism plays a role in the Simon task, a spatial version of the Stroop task. If the ISPC effect does rely on an associative mechanism, the relevant associations are acquired very rapidly. They also appear to be independent of the color in which words are presented, as an association between the compound stimulus of word + color (e.g., GREEN in red ink) and a response (e.g., "red") would not be expected to produce effects on W that are independent of C, the dis-

Table 5
Experiment 2B: Mean Estimates of W and C, With Standard Deviations (*SD*s)

	Parameter			
	W		C	
Proportion Congruent	*M*	*SD*	*M*	*SD*
Mostly congruent	.47	.19	.71	.22
50/50	.37	.14	.70	.20
Mostly incongruent	.28	.17	.66	.21

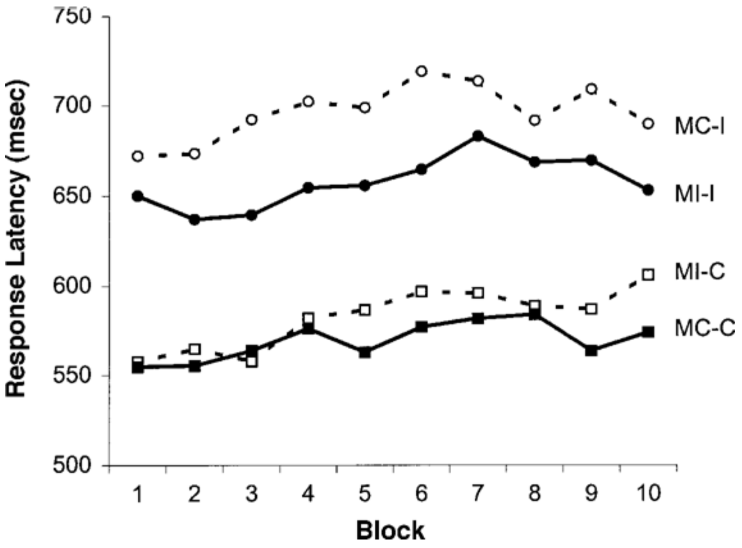

Figure 2. Experiment 3: Response latencies across blocks for congruent items in mostly congruent (MC-C) and mostly incongruent (MI-C) conditions, and for incongruent items in mostly congruent (MC-I) and mostly incongruent (MI-I) conditions.

sociations that we observed. A second possibility is that, rather than an associative mechanism, early processing of individual words triggers inhibitory processes that curtail full reading of the word or block access of any word-reading processes to the response system. That is, reading particular words may be inhibited when they represent an MI test condition.

Regardless of the mechanism involved (e.g., associative or item-specific inhibition), our results suggest automatic control of automatic processes (word reading). That is, it seems unlikely that the participants were effortfully and strategically modulating processing of MI words versus MC words; rather, differential effects of word reading on responding for MI words versus MC words likely arose automatically. Automatic control of the influence of word reading is of particular interest for understanding Stroop performance in special populations such as older adults. Perhaps control of word reading at the item level depends on a mechanism that operates even when a more central, task-demand mechanism fails. The idea of "automatic control" is an intuitively appealing one, which we plan to explore in future research.

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(Manuscript received October 23, 2001;
revision accepted for publication July 12, 2002.)