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Dissociating Levels of Cognitive Control: The Case of Stroop Interference

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Abstract

Attention is often imperfect; cognitive control is needed to counteract the tendency to attend to distractors that are incompatible with current goals. Cognitive psychologists have long explored cognitive control by examining Stroop interference—the slowed naming of colors on incongruent trials (e.g., "RED" displayed in blue ink), as compared to congruent trials (e.g., "RED" displayed in red ink), in the color-word Stroop task. The magnitude of interference reflects the effectiveness of cognitive control, but it does not reveal the precise processes used to minimize attention to the distracting word. The need for experimental approaches that accomplish this objective is underscored by the existence of qualitatively different cognitive control processes. Prior accounts stressed the use of top-down filtering processes at a task- or list-wide level to avoid word reading, but recent findings have shown that control of word reading is sometimes stimulus-driven—that is, triggered by the processing of stimuli or stimulus features. In this article, I highlight the critical findings that dissociate top-down and stimulus-driven control in the Stroop task, dissociations that are central to the view that cognitive control operates at multiple levels.

Keywords

cognitive control, Stroop, stimulus-driven control, top-down control, proportion congruence

The terms "stimulus-driven" and "environmentally triggered" have long been used to describe behavior (e.g., Pavlov, 1927; Watson, 1913). Perhaps surprisingly, these terms are now used to describe cognitive control, the biasing of attention away from distractors in favor of goal-relevant information. Cognitive control was classically thought of as a slow and strategic process (e.g., Posner & Snyder, 1975; Shiffrin & Schneider, 1977) that is initiated in a top-down (i.e., internal, goal-driven) fashion. However, recent evidence has pointed to qualitatively different cognitive-control processes that are quickly and flexibly triggered by the presence of particular stimuli (e.g., Bugg, Jacoby, & Chanani, 2011; Jacoby, Lindsay, & Hessels, 2003) or stimulus features (e.g., Bugg, Jacoby, & Toth, 2008; Crump, Gong, & Milliken, 2006). The purpose of this article is to introduce readers to emerging empirical evidence within the Stroop literature that supports a broader conceptualization of cognitive control, one that views control as operating at multiple, dissociable levels, from the level of individual items (i.e., stimulus-driven control) to more global levels, such as the level of a list (i.e., top-down control).

Cognitive Control Inside and Outside of the Laboratory

In the laboratory, researchers frequently use the Stroop color-naming task (Stroop, 1935) to assess cognitive control. Of primary interest is interference, the slowing of responses that is found on incongruent trials (e.g., "RED " displayed in blue ink) as compared to congruent trials (e.g., "RED" displayed in red ink; MacLeod, 1991). The magnitude of interference reflects the effectiveness of cognitive control, but it does not reveal the precise processes used to minimize attention to the distracting word. A reduction in interference could result from the use of a top-down process, such as filtering, whereby one controls the influence of the word by attempting to ignore it throughout a task or series (i.e., list) of trials. Such an approach may be optimal when one knows that most stimuli will be interfering (i.e., incongruent). Indeed, in many everyday situations, humans bank on advance information that allows them to adjust attention before an interfering stimulus is even encountered, thereby minimizing its influence. For example, students are frequently faced with the challenge of attending to a lecture in the face of distractions (e.g., a Facebook page on a neighboring student's laptop). After several days of lecture, one can anticipate the occurrence of such distractions and apply a top-down filter to ignore them.

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Interference is not always predictable, however, including in the Stroop task, in which different trials often require differing degrees of control (e.g., 50% of items may be congruent). Recent accounts posit a cognitive-control process that operates in such situations (e.g., Braver, Gray, & Burgess, 2007). Specifically, stimulus-driven control of the distracting word occurs quickly and flexibly after the onset of the stimulus. In real-world contexts, such as a classroom, one also finds distractors (e.g., conversations of neighbors) that emerge unpredictably and are differentially interfering. Some types of conversations might usually be distracting, whereas others might usually be facilitative (e.g., they relate to the lecture). Stimulus-driven accounts stress the exploitation of this *item-specific* information. For instance, if Barbara's conversations tend to be distracting, then when one hears Barbara's voice, it can serve as a trigger to boost control by quickly attempting to shift attention away from her conversation. By contrast, if Lucy's conversations tend to be facilitative, Lucy's voice may serve as a signal to permit greater attention to her conversation. The key is that a top-down filter that is indiscriminately (globally) applied to all distractions (e.g., conversations) is not being used; rather, a more flexible, stimulus-driven control process is active.

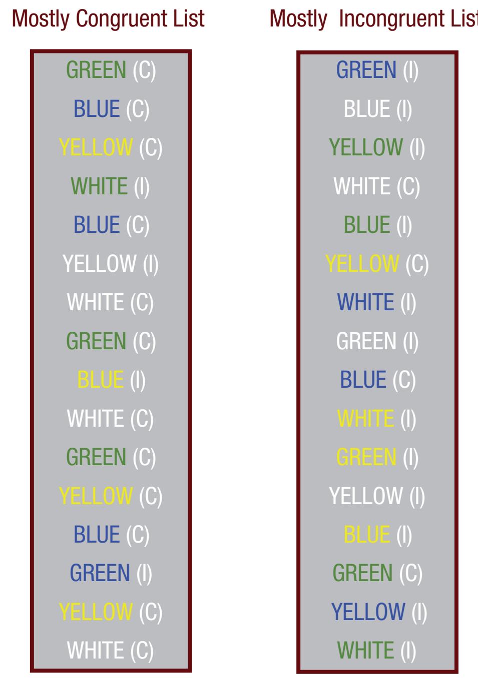

Fig. 1. Stimulus lists in a traditional design for a list-wide proportion congruence manipulation. C = congruent; I = incongruent.

Top-Down Control of Interference

Cognitive control sometimes involves use of advance information to bias (i.e., guide) attention away from distractors (e.g., a filtering strategy). Logan and Zbrodoff (1979) implemented a straightforward list-wide proportion congruence manipulation for measuring the influence of cognitive-control strategies on Stroop interference. The logic behind this manipulation is that disproportionately presenting congruent trials (i.e., using a mostly congruent stimulus list; left column in Fig. 1) encourages fuller processing of the words, which facilitates performance on most trials. Disproportionately presenting incongruent trials (i.e., using a mostly incongruent stimulus list; right column in Fig. 1) biases attention away from the words because they produce conflict on most trials (cf. Melara & Algom, 2003). Stroop interference is significantly reduced with the mostly incongruent stimulus list as compared to the mostly congruent list (see Fig. 2; e.g., Bugg & Chanani, 2011; Bugg, McDaniel, Scullin, & Braver, 2011; Kane & Engle, 2003; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Logan, Zbrodoff, & Williamson, 1984; Lowe & Mitterer, 1982; West & Baylis, 1998). This list-wide proportion congruence effect has become a widely used measure of "list-level" control, the engagement of a global, top-down process for minimizing interference.

Stimulus-Driven Control

Jacoby and his colleagues (Jacoby et al., 2003) developed a variant of the list-wide proportion congruence manipulation that seemed to capture stimulus-driven control, particularly the fast and flexible control of attention on an item-by-item basis. A unique feature of their item-specific manipulation of proportion congruence was that words, rather than lists, were designated as mostly congruent or mostly incongruent. For example, the words "GREEN" and "WHITE" were mostly congruent items, whereas the words "YELLOW" and "BLUE" were mostly incongruent items. As shown in Figure 3, these words were intermixed and randomly presented to participants. Thus, participants could not reliably predict whether the likelihood of interference on any given trial was high or low. Still, the researchers found significantly less interference for

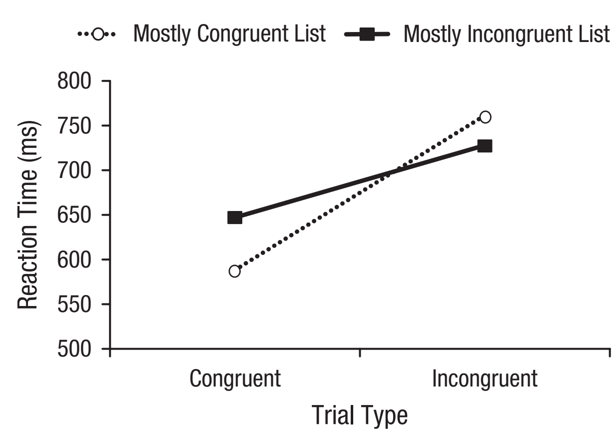

Fig. 2. The list-wide proportion congruence effect: Interference is reduced for the list-wide mostly incongruent condition as compared to the list-wide mostly congruent condition. Data from Bugg, McDaniel, Scullin, and Braver (2011; Experiment 1).

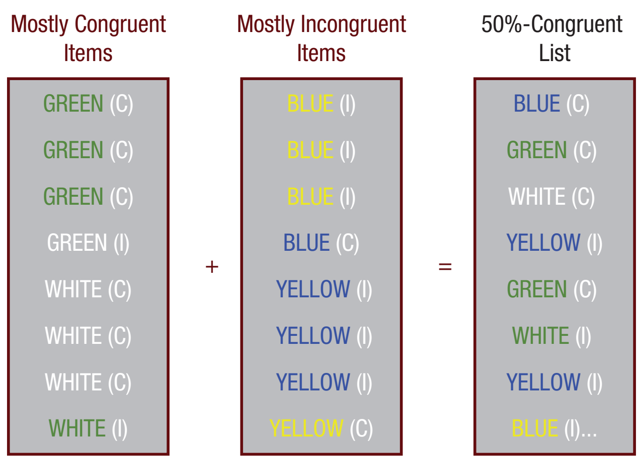

Fig. 3. Stimulus lists in a standard design for an item-specific proportion congruence manipulation. C = congruent; I = incongruent.

mostly incongruent items than for mostly congruent items, a pattern termed the *item-specific proportion congruence* (ISPC) effect (see Fig. 4).

The fact that different levels of interference were found for different items within the same 50%-congruent list (i.e., the ISPC effect) could not be accounted for by a global (i.e., uniform), list-level control process. It appeared instead that attention to the words was controlled on an item-by-item basis. Moreover, because the identity of each word (and whether it was mostly congruent or mostly incongruent) could not be determined until the item was presented, modulation of attention had to occur after the onset of the stimulus.

Much of the excitement surrounding the discovery of "item-level" control centered on how rapidly and flexibly it operates, in sharp contrast to list-level control. According to an alternative account, however, the excitement was premature. This account attributed the ISPC effect to the use of a mechanism that might be thought of as the antithesis of cognitive control—simple associative learning (Schmidt & Besner, 2008). By this *contingency account*, participants learn to predict the responses that are frequently paired with particular words (e.g., a response of "green" when the mostly congruent item "GREEN" is presented, and a response of "yellow" when the mostly incongruent item "BLUE" is presented; cf. Melara & Algom, 2003), which speeds responses on two of the four types of trials (congruent trials for mostly congruent items and incongruent trials for mostly incongruent items; see Fig. 4), producing the ISPC pattern. It is difficult to disentangle this account from an account of item-level *control*, which posits that participants use the distracting word as a signal of the likelihood of interference for that item and modulate control accordingly (e.g., the word "GREEN" signals participants to process the word more fully, and the word "BLUE" signals participants to quickly curtail word processing). (Indeed, Jacoby and his research group acknowledged that both mechanisms might be contributing; Jacoby et al., 2003.)

Using a simple twist on the standard ISPC manipulation, I and my colleagues (Bugg, Jacoby, & Chanani, 2011, Experiment 2) disentangled the two mechanisms. Instead of assigning items to mostly congruent or mostly incongruent sets on the basis of the words in a color-word Stroop task, we used a picture-word Stroop task and assigned items to sets on the basis of the relevant dimension, the to-be-named pictures. For example, pictures of birds and cats were mostly congruent, and pictures of dogs and fish were mostly incongruent (see Fig. 5). Critically, this meant that the dimension that signaled the proportion congruency of each item (i.e., the picture) differentially predicted the likelihood of interference but perfectly predicted the correct response for all items. Therefore, the obtainment of an ISPC effect with this design could not be due to participants learning to predict the responses that were associated with each picture. The contingency account would predict equivalent interference across the mostly congruent and mostly incongruent items.

To understand why this is the case, consider the upper row of Table 1. The relevant dimension dictates which items are mostly congruent and which are mostly incongruent, and that dimension is 100% predictive of the response in *all* four trial types (congruent trials for mostly congruent items, incongruent trials for mostly congruent items, congruent trials for mostly incongruent items, and incongruent trials for mostly incongruent items). Thus, when one compares performance between the mostly congruent and mostly incongruent items, this comparison is *not* confounded by variations in contingency. This contrasts starkly with the lower row of the table, which illustrates the typical design in which words dictate whether items are mostly congruent or mostly incongruent, and the word is highly predictive of the response in only two of the four trial types. In this case, any comparison of performance between the mostly congruent and mostly incongruent items is confounded by variations in contingency.

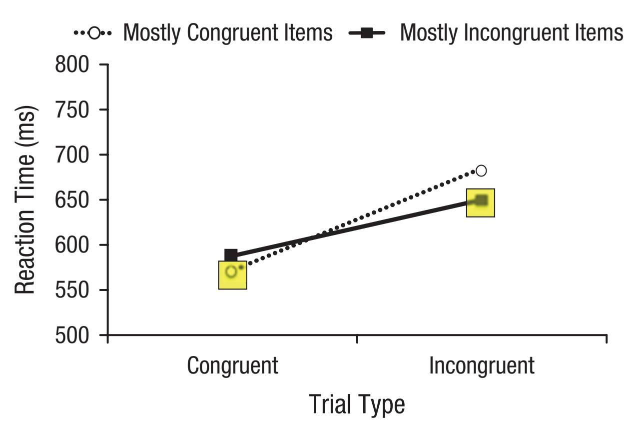

Fig. 4. The item-specific proportion congruence effect: Interference is reduced for the item-specific mostly incongruent condition as compared to the item-specific mostly congruent condition. Trials on which responses can be predicted via simple associative-learning are highlighted. Data from Jacoby, Lindsay, and Hessels (2003).

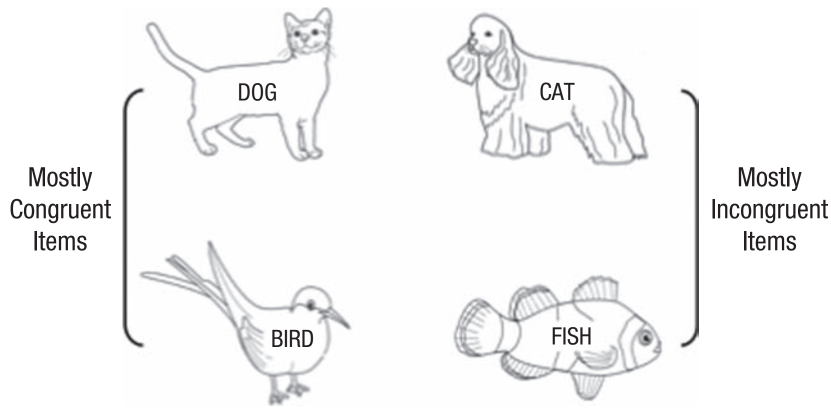

Fig. 5. Sample pictures from the mostly congruent and mostly incongruent sets of items in Bugg, Jacoby, and Chanani (2011).

Contrary to the predictions of the contingency account, our results (Bugg, Jacoby, & Chanani, 2011; Experiment 2) demonstrated a significant ISPC effect. Interference was greater for mostly congruent items than for mostly incongruent items, a result consistent with the idea that item-level control attenuated word reading for the mostly incongruent items.

Further corroborating the role of item-level control in the obtainment of this ISPC effect was the following evidence. First, this effect had a different form than the effect discovered by Jacoby et al. (2003) (see Fig. 4), to which associative learning may have contributed. As shown in Figure 6, the effect was driven almost entirely by a difference in response times for mostly congruent items and for mostly incongruent items on incongruent trials. This is the (interaction-based) pattern that has been suggested to reflect the modulation of word reading via item-level control, "because incongruent trials should be more affected by attention, given that the majority of the Stroop effect is interference" (Schmidt & Besner, 2008, p. 516). Second, we (Bugg, Jacoby, & Chanani, 2011, Experiment 2) showed novel evidence for the transfer of control. As shown in Figure 7, the ISPC effect was obtained for a set of 50%-congruent transfer items that were introduced in a final block of trials, indicating that participants generalized the control settings they had learned for mostly congruent items (e.g., cats) and mostly incongruent items (e.g., dogs) to new instances of these items. Because these new instances were presented equally frequently (as congruent and incongruent trials), this finding was important in ruling out alternative, frequency-based accounts (e.g., Logan, 1988).

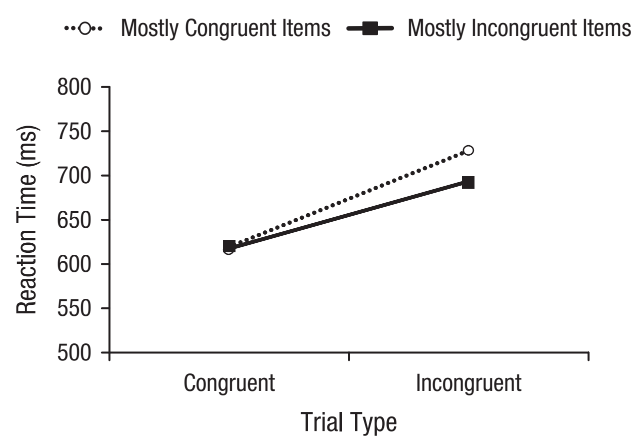

Fig. 6. Item-specific proportion congruence effect for which the contribution of simple associative learning has been controlled. Data from Bugg, Jacoby, and Chanani (2011).

Table 1. Predictability of Responses on Congruent and Incongruent Stroop Trials as a Function of Item-Specific Proportion Congruency and the Dimension That Signals Item-Specific Proportion Congruency

	Mostly congruent item		Mostly incongruent item	
Dimension	Congruent trial	Incongruent trial	Congruent trial	Incongruent trial
Relevant (picture or color)	High predictability (1.00)	High predictability (1.00)	High predictability (1.00)	High predictability (1.00)
Irrelevant (word)	High predictability (.75)	Low predictability (.25)	Low predictability (.25)	High predictability (.75)

Note: Values in parentheses indicate the likelihood of predicting the correct response on the basis of the signal.

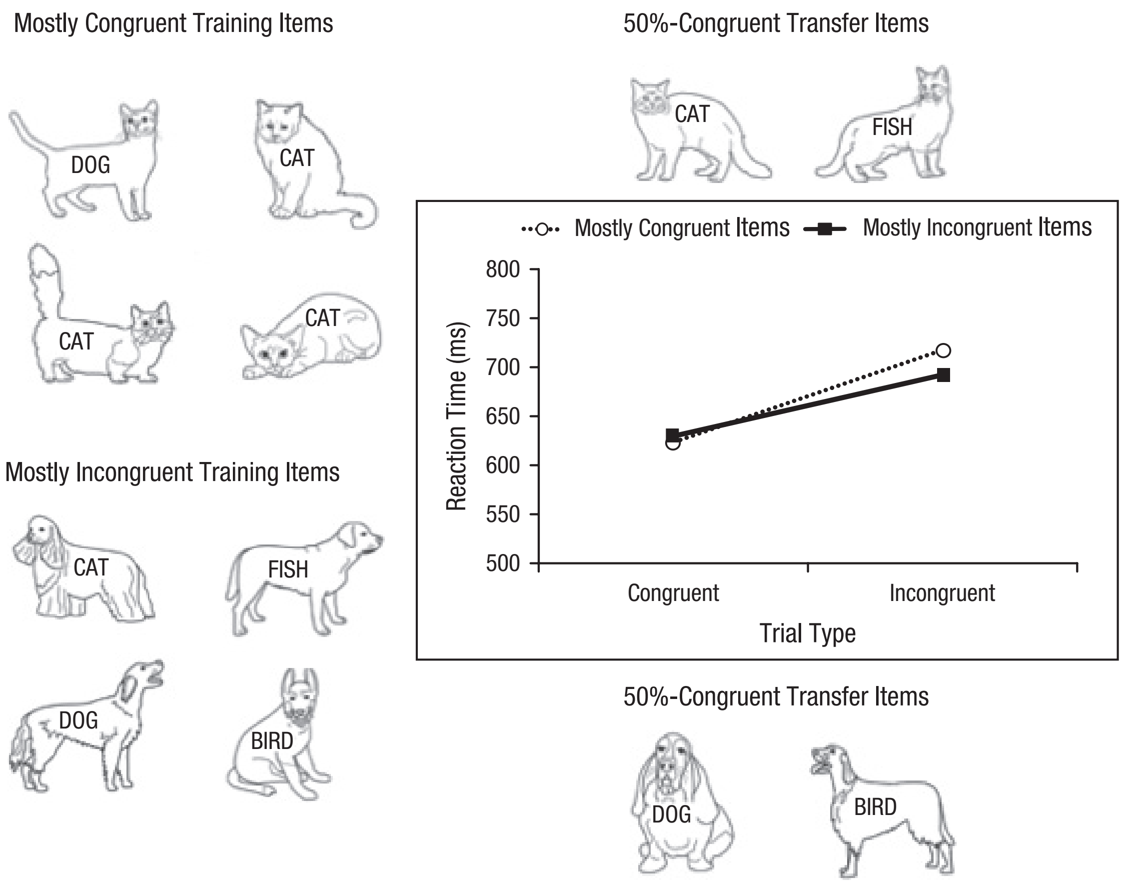

Fig. 7. Results and sample training and transfer items from Bugg, Jacoby, and Chanani (2011). Note that the transfer items differ from the training items presented during the initial blocks of the task but are from the same categories (e.g., cats, dogs). Importantly, the transfer items were 50% congruent, meaning that they were presented equally frequently with a congruent word as with an incongruent word. The graph depicts the item-specific proportion congruence effect that was observed for the transfer items. Interference was lower for 50%-congruent items that were from the same category as the item-specific mostly incongruent (ISMI) items (e.g., dogs) than for 50%-congruent items that were from the same category as the item-specific mostly incongruent (ISMC) items (e.g., cats).

Could List-Level Control Be Item-Level Control in Disguise?

One of the major theoretical implications of the discovery of stimulus-driven control is that it calls for a reexamination of effects that have previously been attributed to top-down control. Indeed, a fresh look at the list-wide proportion congruence manipulation reveals that it is perfectly confounded with ISPC (See Fig. 1). Might the list-wide proportion congruence effect be accounted for by item-level control?

Results from an initial study suggested it could be (Bugg et al., 2008). The critical evidence stemmed from performance on a set of 50%-congruent items that were embedded within the mostly congruent and mostly incongruent lists, lists whose proportion congruency was determined by a separate set of items that were 75% or 25% congruent, respectively (see Fig. 8). Unlike the mostly congruent and mostly incongruent items, the 50%-congruent items had no item-specific proportion congruence bias (they were equally likely to be congruent or incongruent in both lists). They did, however, reside within mostly congruent or mostly incongruent lists, and therefore had different list-level biases. Obtainment of a list-wide proportion congruence effect for the mostly congruent and mostly incongruent items would be ambiguous—it could reflect list-level or item-level mechanisms. By contrast, obtainment of the effect for the 50%-congruent items would be indicative of list-level control, independent of item-specific influences.

The list-wide proportion congruence effect was found *only* for the mostly congruent and mostly incongruent items (see also Blais & Bunge, 2010), indicating that participants did not implement global list-level control. This was a surprising finding, as it suggested that the classic list-wide proportion congruence effect might be an ISPC effect in disguise, which challenges extant models (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). In other words, there may be no such thing as list-level control of Stroop interference; item-level

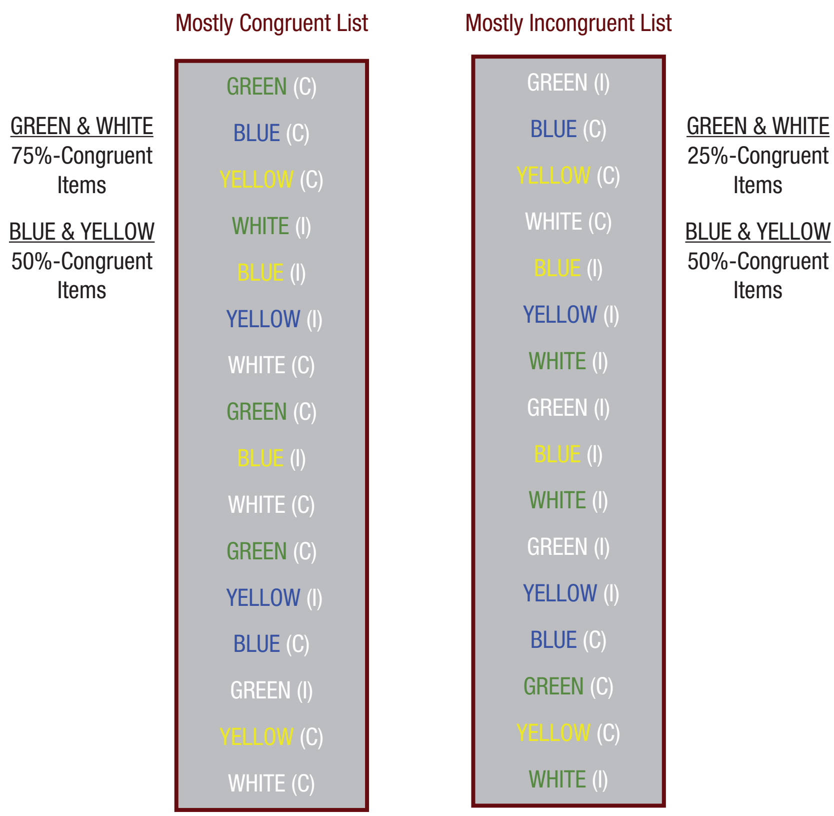

Fig. 8. Stimulus lists in a newer design for a list-wide proportion congruence manipulation. The lists include 50%-congruent items ("BLUE" and "YELLOW"), which permit an examination of list-level control independent of item-specific influences. Notice that the 50%-congruent items occur equally often as congruent and incongruent items across both lists.

control may be sufficient to explain the putative contribution of list-level control (see Blais, Robidoux, Risko, & Besner, 2007, for a computational model that adopts this assumption).

Given these stunning implications, replication was warranted. I and Chanani (Bugg & Chanani, 2011) speculated that participants in the prior study may not have engaged list-level control because interference could be minimized on most trials (75%) simply by exploiting associations within the list. The set of items that I and other colleagues (Bugg et al., 2008) had used to create the list-wide bias (25% congruent vs. 75% congruent) was composed of only two items (see Fig. 8; see also Blais & Bunge, 2010), meaning that participants could learn to predict the responses typically associated with these items, possibly bypassing control. Using a picture-word Stroop task, Chanani and I increased the set size to four so the responses on the incongruent trials could not be predicted. A significant list-wide proportion congruence effect was then observed for the mostly congruent and incongruent items *and* for the 50%-congruent items, with the last providing unambiguous evidence for the contribution of list-level control to the list-wide proportion congruence effect (see also Fernandez-Duque & Knight, 2008; Hutchison, 2011).

Although this finding challenges item-level models (e.g., Blais et al., 2007), it is consistent with models that accommodate both item-level and pathway-level (global) control adjustments (e.g., Verguts & Notebaert, 2009; cf. Egner's, 2008, idea of multiple conflict-control loops that operate in parallel). Some may, however, question whether list-level control is specific to picture-word stimuli, for which the word may be more easily filtered in a top-down fashion.

I and my colleagues (Bugg, McDaniel, et al., 2011) addressed this concern by investigating whether color-naming performance on neutral trials with non-color words (e.g., GOLF, ARM) was affected by list-wide proportion congruence. We manipulated proportion congruence by using a large set of color-word Stroop stimuli, such that responses could not be predicted on incongruent trials. Participants responded significantly faster on neutral trials in the mostly incongruent list condition than in the mostly congruent list condition. Because neutral words were 100% neutral across lists (i.e., they did not have differing levels of ISPC), this difference suggested the use of list-level control.

In a second experiment, we sought converging evidence for list-level control by examining a potential performance *cost*. It was predicted that performance on a secondary task (i.e., remembering to press a key in response to a target stimulus) would be significantly worse in the mostly incongruent list if the secondary task required participants to attend to the word dimension (i.e., if the target stimulus was a word), which was presumably being filtered. In confirmation of this prediction, participants' performance was significantly worse in the mostly incongruent list than the mostly congruent list when the target stimulus was the neutral word "HORSE." Because the word "HORSE" was equally neutral in the mostly congruent and mostly incongruent lists, differential performance across the list conditions implies the use of a list-level control process that globally filters words to a greater degree when most trials within a list condition are interfering than when most are not interfering. These findings establish that list-level control can be dissociated from item-level control in the color-word Stroop task, and they lend further support to the view that participants engage list-level control when they cannot simply rely on associative learning.

Concluding Remarks

Cognitive control operates at multiple, dissociable levels. Having the tools to dissociate such levels of control opens up exciting avenues for future research. Manipulations (e.g., divided attention) or individual-difference factors (e.g., age; disorders such as ADHD) that have previously been shown to affect cognitive control may have distinctive effects on different levels of control. To comprehensively address such issues, we should ideally use tools that can dissociate levels of cognitive control in a broader set of domains, including stopping and task switching. Investigators are beginning to identify such tools (see Crump & Logan, 2010, for initial evidence of stimulus-driven control of task-set retrieval using a proportion task-switch manipulation).

Although I focused on differentiating list-level from item-level control on the basis of whether participants do or do not have advance information about the likelihood of interference (i.e., proportion congruency), future research is needed to evaluate whether other distinctions might expand our understanding of the differences between levels of control (e.g., strategic vs. nonstrategic; explicit vs. implicit). For example, does list-level control involve willed or voluntary control of word reading, whereas item-level control does not depend on will? Such a distinction is reminiscent of the "emitted" versus "elicited" distinction that characterized operant conditioning and classical conditioning, respectively, and therefore compels the question of whether classical conditioning principles might be used to explain the (relatively abstract) attentional adjustments that underlie stimulus-driven control.

Recommended Reading

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). (See References). An accessible introduction to the distinctions between proactive and reactive control mechanisms, for which list-level and item-level control, respectively, can be viewed as examples.

Crump, M. J. C., & Milliken, B. (2009). The flexibility of context-specific control: Evidence for context-driven generalization of item-specific control. *The Quarterly Journal of Experimental Psychology, 62*, 1523–1532. A study that, although outside the scope of the current review, provides evidence for stimulus-driven control using a context-specific proportion congruence manipulation, raising questions about the similarities and differences between context-level control and item-level control.

Lindsay, D. S., & Jacoby, L. L. (1994). (See References). A paper presenting an elegant application of the process-dissociation procedure to the list-wide proportion congruence manipulation, with process estimates showing that its effect is entirely on the word-reading process (which was later replicated for the item-specific proportion congruence manipulation; Jacoby et al., 2003).

Melara, R. D., & Algom, D. (2003). (See References). A must-read paper for researchers interested in Stroop that provides compelling evidence showing that participants detect correlations between words and colors (as is the case when proportion congruence is manipulated, and even when it is not) and use information conveyed by distractors (e.g., about whether responses likely match the word) to optimize performance.

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Declaration of Conflicting Interests

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