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Context-specific learning and control: The roles of awareness, task relevance, and relative salience

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Abstract

The processes mediating dynamic and flexible responding to rapidly changing task-environments are not well understood. In the present research we employ a Stroop procedure to clarify the contribution of context-sensitive control processes to online performance. In prior work Stroop interference varied as a function of probe location context, with larger Stroop interference occurring for contexts associated with a high proportion of congruent items [Crump, M. J., Gong, Z., & Milliken, B. (2006). The context-specific proportion congruent stroop effect: location as a contextual cue. *Psychonomic Bulletin & Review, 13*, 316–321.] Here, we demonstrate that this effect does not depend on awareness of the context manipulation, but that it can depend on attention to the predictive context dimension, and on the relative salience of the target and predictive context dimensions. We discuss the implications of our results for current theories of cognitive control.

Keywords: Cognitive control; Implicit learning; Automatic; Context; Conflict monitoring; Selective attention; Performance; Awareness; Stroop; Proportion congruent

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1. Introduction

Research in the field of cognitive control is directed at processes that select information in support of efficient performance. Selection demands arise because many task environments contain an abundance of both relevant and irrelevant information, and efficient performance requires behavior to be controlled by task-relevant rather than task-irrelevant information. Researchers have often distinguished between controlled and automatic influences over attentional selection (Posner & Snyder, 1975; Shiffrin & Schneider, 1977). Controlled processes are thought to underlie relatively slow shifts in attention in accord with top-down goals, whereas automatic processes are thought to underlie much faster shifts in attention that are driven by salient properties of the stimulus. By this view, the need for relatively slow, deliberate control over selection arises when automatic processing of salient stimulus properties would otherwise lead an uncontrolled selection

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process astray of task goals. In other words, voluntary control over selection is seen as the alternative to allowing selection to be guided by stimulus salience.

In contrast to this view, there has been increasing interest in the idea that learning and memory processes can express themselves in performance rapidly and involuntarily to control attentional selection. Indeed, evidence that control can be outsourced to incidental or contextual properties of the task environment has been recently demonstrated in task switching (Mayr & Bryck, 2005), visual search (Chun, 2000), flanker (Cohen, Fuchs, Bar-Sela, Brumberg, & Magen, 1999; Corballis & Gratton, 2003; Miller, 1987), and Stroop paradigms (Crump, Gong, & Milliken, 2006; Jacoby, Lindsay, & Hessels, 2003). The specific aim of the present study was to examine further a recently reported context-sensitive control effect measured using a Stroop procedure (Crump et al., 2006), and in particular to highlight several important boundary conditions of this effect. To set the context for the empirical work described below, a brief review of the use of Stroop interference to measure cognitive control is now presented.

In a typical Stroop task (Stroop, 1935) participants name aloud the ink-color of a color word (for a review see MacLeod, 1991). The Stroop effect refers to the finding that color-naming proceeds faster for congruent items (red in RED) than incongruent items (red in BLUE). The Stroop effect is theoretically interesting because it provides a useful tool for measuring processes controlling the selection of relevant and irrelevant information during performance. In general, large Stroop effects imply inefficient selection of task-relevant information, while small Stroop effects imply efficient selection of task-relevant information. Consequently, modulations of the Stroop effect provide a window into the control processes that mediate selection during task performance.

It is well known that the Stroop effect varies as a function of the proportion of congruent items in a block of trials (Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982; West & Baylis, 1998). In general, high proportion congruent blocks of trials produce larger Stroop effects than low proportion congruent blocks of trials. Proportion congruent Stroop effects have been interpreted by many researchers to reflect an influence of voluntary control over selection.

For example, participants might employ different strategies with regard to word reading between high and low proportion congruent blocks of trials (Logan, Zbrodoff, & Williamson, 1984; Lowe & Mitterer, 1982). A strategy that emphasizes filtering word reading would be appropriate for a low proportion congruent block of trials, whereas a strategy that allows word reading to guide response selection might be appropriate for a high proportion congruent block of trials. A related view is that high proportion congruent blocks of trials place greater demand on processes governing maintenance of the ink-color naming task set (West, 1999). Indeed, Kane and Engle (2003) demonstrate that individual differences in working memory capacity predict the extent to which increases in proportion congruent influence the size of the Stroop effect. Generally speaking, the idea that proportion congruent effects on Stroop interference reflect changes in voluntary control fits well with the notion that a goal-directed, central task demand mechanism is responsible for selectively weighting the contribution of word and color information to performance (Cohen, Dunbar, & McClelland, 1990; Botvinick, Braver, Barch, Carter, & Cohen, 2001).

At the same time, other researchers have argued that the influence of proportion congruent on the Stroop effect reflects an involuntary learning process that is sensitive to the correlation of word and color dimensions. For example, Dishon-Berkovits and Algom (2000) used a word–word (i.e., cities and countries) variant of the Stroop procedure and demonstrated that Stroop effects were observed only when the target and distractor dimensions were positively or negatively correlated. Interestingly, Stroop effects were not observed when the target and distractor dimensions were uncorrelated. From an information theoretic perspective, Melara and Algom's (2003) tectonic theory of Stroop effects argues that attentional resources are automatically directed to stimulus dimensions that contain potentially relevant information. By this view, introducing correlations between target and distractor dimensions (e.g., distractor dimensions in a high proportion congruent condition positively predict target dimensions) causes the distractor dimension to carry potentially relevant information about the target dimension. As a result, failures to select the target dimension occur because attentional resources are directed to the potentially informative distractor dimension. In this way, proportion congruent modulations to the Stroop effect need not reflect changes in voluntary control, but could instead reflect changes in the amount of information extracted from the distractor dimension as a function of its correlation with the target dimension.

On a similar theme, Jacoby et al. (2003) challenged the idea that proportion congruent influences on the Stroop effect are necessarily mediated by voluntary means. Jacoby et al., used an item-specific proportion congruent manipulation (ISPC) in which one set of Stroop items (e.g., WHITE, RED, and YELLOW word/color combinations) was associated with a high likelihood of congruency, and another set of Stroop items (e.g., BLACK, BLUE, and GREEN) was associated with a low likelihood of congruency. Both item types were mixed together in the same block of trials. As a result, participants could not predict the likelihood of congruency in advance of each trial, and therefore different Stroop effects for high and low proportion congruent item types could not reasonably be attributed to voluntary strategy shifts that occur in advance of stimulus onset. Yet, this is exactly the effect that was observed. Jacoby et al., labeled this result the item-specific proportion congruent (ISPC) effect.

Jacoby et al. (2003) forwarded two explanations for the ISPC effect. On the one hand, differences in word-reading between the high and low proportion congruent item types could reflect a kind of "automatic control" over performance. According to this view, encoding of the item type could rapidly trigger an item-specific set of attention procedures that modulate the contribution of word-reading to color-naming performance. On the other hand, Jacoby et al. (2003) pointed out that particular words were not only predictive of congruency, but were also predictive of particular responses. As a result, the ISPC effect they report could reflect stronger learning of particular stimulus–response mappings for frequently presented than less frequently presented items. Note that a simple associative learning account of the ISPC effect would not require additional inferences about involuntary influences over selection.

To address whether the ISPC effect is determined entirely by learning of associations between particular words and responses, Crump et al. (2006) varied proportion congruent between different contexts (e.g., location or shape) in which Stroop target colors could appear. The critical property of the procedure was that incidental contextual cues predicted likelihood of congruency, but did not predict particular responses. For example, in the experiment that used location as a contextual cue, participants were presented with a color word prime (displayed in white) at fixation, followed by a color patch probe that appeared above or below fixation. Probes that appeared above fixation were highly likely to be congruent with the preceding prime word, and probes that appeared below fixation were highly likely to be incongruent with the preceding prime word. Importantly, the location of the color patch probe was randomized from trial to trial, which meant that participants could not possibly know whether the probe was "likely to be congruent" or "likely to be incongruent" until its appearance. Further, the context-specific proportion congruent manipulation removed any association between particular words and responses, and between particular contexts and responses. Nonetheless, the Stroop effect was larger in the high proportion congruent location context than in the low proportion congruent location context. Crump et al., labeled this result a context-specific proportion congruent (CSPC) Stroop effect.

The CSPC Stroop effect reported by Crump et al. (2006) had several notable properties. First, participants appeared not to be aware of the CSPC manipulation. Second, the CSPC effect was observed when location served as a contextual cue, but not when shape (square or circle) served as a contextual cue. Finally, analysis of trial sequences demonstrated that the CSPC Stroop effect did not depend on the nature of the preceding trial. Taken together, these properties implicate a learning and memory process that controls online performance selectively for certain contextual dimensions and not others, but that does so rapidly and involuntarily upon stimulus onset. This intriguing combination of selective, but yet involuntary, control over behavior led us to pursue the boundary conditions of this effect further.

In Experiments 1a and 1b we tested the possibility that CSPC Stroop effects occurred for location but not shape contexts because participants were only aware of the contingency manipulation for the location contexts. The results suggest that this was not the case. In Experiment 2, we examined whether the CSPC effect can be found for a contextual dimension other than location (i.e., shape) when that contextual dimension is made task-relevant. Indeed, we found this to be the case. Finally, in Experiment 3, we learned that the CSPC effect is sensitive to dimensional salience, as it occurs for the usual variant of the Stroop task (i.e. name color and ignore word), but not for the reverse Stroop task (i.e., name word and ignore color). The general procedure used across these experiments is depicted in Fig. 1.

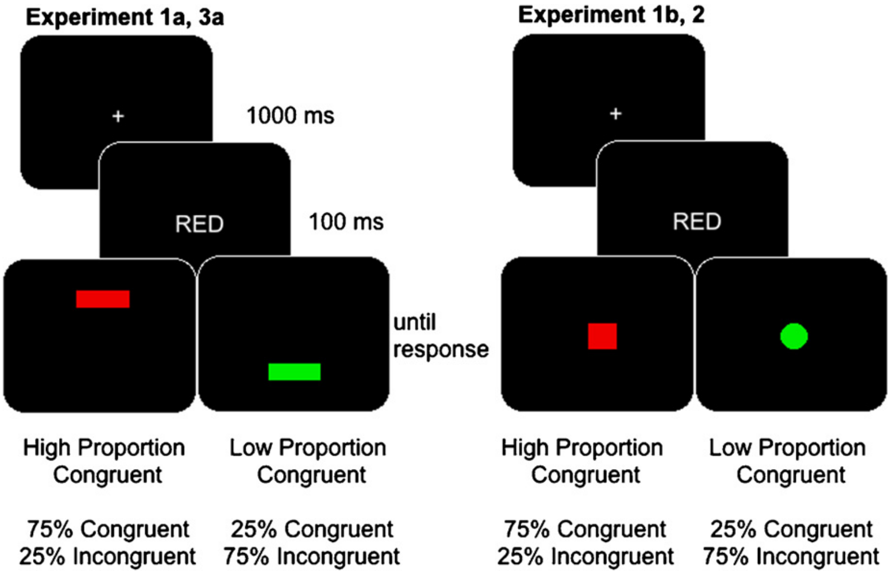

Fig. 1. Depicts a schematic of the trial sequence for Experiments 1a and 3a where location is the contextual cue, and Experiments 1b and 2 where shape is the contextual cue. Experiment 3b was exactly the same as Experiment 3a, except the prime and probe stimuli were reversed. Participants task in all experiments was to verbally identify the probe stimulus.

2. Experiment 1a and 1b: The role of awareness

Crump et al. (2006) reported that participants in their experiments appeared to be unaware of the context-specific proportion congruent manipulation. In particular, explicit awareness of the proportion congruent manipulation was measured at the end of each experimental session. Participants were shown examples of congruent and incongruent trials appearing in each location/shape context, and were asked to estimate the proportion of congruent items appearing in each context. Participants' estimates of proportion congruent did not differ for the high and low proportion congruent contexts, indicating that they were not able to explicitly describe the CSPC manipulation. This finding strengthened the claim that CSPC effects are not mediated by voluntary control processes.

Although participants' estimates of the proportion congruent manipulation suggest a lack of awareness, the format of the questionnaire may have been confusing to participants. For example, it is well known that people reason poorly with probabilities as compared to natural frequencies (Gigerenzer, 2002; Gigerenzer & Hoffrage, 1995; Kahneman & Tversky, 1982; Kahneman & Tversky, 1996). As the questionnaire used a probabilistic format to assess participants' knowledge of the proportion congruent manipulation, it is possible that their inability to describe the proportion congruent manipulation reflected an inability to reason with probabilistic information, rather than a fundamental lack of awareness of the proportion congruent manipulation. As a result, the possibility remains that the location-based CSPC effect depended on participants' awareness of the proportion congruent manipulation that was not accurately measured by the awareness questionnaire. In line with this idea, a shape-based CSPC effect might not have occurred because participants remained unaware of the association between shape cues and proportion congruent, perhaps because the two shape cues were less discriminable from each other than the two location cues.

The purpose of Experiments 1a and 1b was to investigate whether awareness of the CSPC manipulation was a critical factor in the earlier reported CSPC study. To this end, we conducted separate location (Experiment 1a) and shape-based (Experiment 1b) CSPC Stroop experiments of the type reported by Crump et al. (2006). Prior to the beginning of each experiment, participants were made explicitly aware of the CSPC manipulation and were required to sign a waiver indicating that they understood which context was high proportion congruent, and which context was low proportion congruent.

Table 1
A description of the context-specific proportion congruent manipulation used for each block of 96 trials across Experiments 1, 2 and 3

Proportion	COLOR				
Congruent	WORD	RED	GREEN	BLUE	YELLOW
High	RED	9	1	1	1
	GREEN	1	9	1	1
	BLUE	1	1	9	1
	YELLOW	1	1	1	9
Low	RED	3	3	3	3
	GREEN	3	3	3	3
	BLUE	3	3	3	3
	YELLOW	3	3	3	3

2.1. Methods

2.1.1. Participants

There were 17 participants in Experiment 1a, and 16 participants in Experiment 1b. All participants were undergraduate students enrolled in psychology courses at McMaster University who volunteered for course credit. All participants spoke English as a first language, had normal color vision, and had normal or corrected to normal visual acuity.

2.1.2. Materials and procedure

This experiment was conducted by 14 trained student experimenters in partial fulfillment of a psychology lab course at McMaster University. Each experimenter tested one participant in Experiment 1a and one participant in Experiment 1b. The remaining participants were tested by the first author and a research assistant.

We followed the same procedure used in Experiments 2a and 2b reported by Crump et al. (2006). The task was a simple priming procedure involving the presentation of a color-word prime, followed by a color patch probe display.[1] There were four equally frequent color-word primes (RED, GREEN, BLUE, YELLOW) displayed in white, and four equally frequent color-patch probes (red, green, blue, yellow). Probes in Experiment 1a were presented in one of two location contexts. Here, each color-patch probe was a colored rectangle 1.6° in height and 5.2° in width that appeared above or below the fixation point (5.7°). Probes in Experiment 1b were presented in one of two shape contexts, with location held constant. Here, each color-patch probe was either a circle (2.6° in diameter) or a square (2.6° in width) that appeared centrally.

Participants in each experiment completed 10 practice trials, followed by four blocks of 96 experimental trials. Each block of 96 trials consisted of 48 trials in which the probe was presented in one location (Experiment 1a) or shape (Experiment 1b) context, and 48 trials in which the probe was presented in the other location or shape context. Importantly, the location or shape context of the probe item was mixed randomly across the block for both experiments. The assignment of high and low proportion congruent conditions to the two location (Experiment 1a) and two shape (Experiment 1b) contexts was held constant across blocks within experimental sessions, but counterbalanced across participants. In each experiment, one of the location or shape contexts was defined as the high proportion congruent condition while the other was defined as the low proportion congruent condition. Within each block, the 48 trials in the high proportion congruent condition consisted of nine presentations of each of the four possible congruent probes (4×9 presentations for a total of 36 trials) and one presentation of each of the 12 possible incongruent probes (12 trials). Similarly, the 48 trials in the low proportion congruent condition consisted of three presentations of each congruent probe (12 trials) and three presentations of each incongruent probe (36 trials: see Table 1 for an overview).

The experiment was conducted on a PC with a 15″ SVGA monitor using MEL experimental software (Schneider, 1988). At the beginning of each experimental session, participants were informed of the

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[1] We employed the prime-probe variant of the Stroop procedure because it produces reliable CSPC Stroop effects, and allows for simple and straightforward manipulations of target processing context. It is also worth noting that pilot studies employing a location-based CSPC design using integrated Stroop stimuli failed to produce statistically reliable CSPC Stroop effects.

context-specific proportion congruent manipulation. To verify that participants understood the instructions, each participant was asked to describe which context was the high proportion congruent context, and which context was the low proportion congruent context. Participants were required to successfully describe these conditions in writing prior to the commencement of the experiment. Participants were seated approximately 57 cm from the computer monitor. At the beginning of each trial, participants were presented with a fixation cross displayed in white against a black background for 1000 ms, followed by a blank interval of 250 ms. Next, a color word prime displayed in white against a black background was presented centrally for 100 ms. Immediately following the prime display, a color patch probe display appeared. Participants were instructed to name the color of the probe as quickly and accurately as possible. The probe was presented on the screen until the participant made a vocal response. Vocal response latencies were recorded using a microphone, and a voice-activated relay timed the response from the onset of the probe display. An experimenter coded each response as correct, incorrect, or spoil. A spoil was defined as a trial in which noise unrelated to the onset of the intended response triggered the voice-key.

2.2. Results

The data from two participants in Experiment 1a and one participant in Experiment 1b were excluded from all analyses because of an equipment failure associated with the voice-key used to collect responses. For the remaining 15 participants in each experiment, RTs greater than 100 ms from correct trials for each condition were submitted to an outlier elimination procedure (Van Selst & Jolicoeur, 1994). Mean RTs were then computed using the remaining observations. The results from both experiments were submitted to a 2 (proportion congruent: high vs low) by 2 (congruency: congruent vs. incongruent) repeated measures ANOVA. RTs and error rates for each condition, collapsed across participants in each experiment, are displayed in Table 2.

2.2.1. Experiment 1a: Location

There was a significant main effect of congruency [$F(1, 14) = 386.70$, $MSE = 403.17$, $p < .0001$]. Responses for congruent trials were faster (468 ms) than responses for incongruent trials (570 ms). More important, the proportion congruent by congruency interaction was significant [$F(1, 14) = 12.11$, $MSE = 184.02$, $p < .005$]. The Stroop effect for the high proportion location condition was larger (114 ms) than the Stroop effect for the low proportion location condition (90 ms). A corresponding analysis of error rates revealed only a main effect of congruency [$F(1, 14) = 11.52$, $MSE = 1.83 \times 10^{-3}$, $p < .005$]; error rates were higher for incongruent trials (.04) than for congruent trials (.01).

Table 2
Mean correct color-naming response latencies (in ms), with standard errors (in parentheses), and error rates for Experiments 1a and 1b

Experiment	Proportion Congruent		Item type: Congruent (C)	Item type: Incongruent (I)	I–C	CSPC effect
1a	High	RT	461	575	114	
		SE	(21)	(23)	(6)	
		ER	.01	.05		
	Low	RT	476	566	90	24
		SE	(20)	(23)	(6)	(7)
		ER	.01	.04		
1b	High	RT	479	557	78	
		SE	(15)	(17)	(11)	
		ER	.01	.04		
	Low	RT	478	562	84	−6
		SE	(17)	(16)	(9)	(7)
		ER	.01	.03		

CSPC, context specific proportion congruent; RT, response time; SE, standard error; ER, error rate.

2.2.2. Experiment 1b: Shape

There was a significant main effect of congruency [$F(1, 14) = 77.80$, $MSE = 748.54$, $p < .0001$]. Responses for congruent trials were faster (478 ms) than responses for incongruent trials (560 ms). Interestingly, there was no significant proportion congruent by congruency interaction. A corresponding analysis of error rates revealed only a main effect of congruency [$F(1, 14) = 6.56$, $MSE = 1.35 \times 10^{-3}$, $p < .05$]; error rates were higher for incongruent trials (.03) than for congruent trials (.01).

2.2.3. Combined RT analysis

To determine whether location cues produced a significantly larger proportion congruent effect than shape cues, a mixed-design ANOVA with experiment (location vs. shape) as a between-participant factor was conducted. The three-way interaction between experiment, proportion congruent and congruency was significant [$F(1, 28) = 9.6$, $MSE = 182.25$, $p < .005$].

2.3. Discussion

The purpose of Experiments 1a and 1b was to determine whether awareness of the CSPC manipulation would influence the CSPC Stroop effect. The results of Experiments 1a and 1b corresponded closely to those of Crump et al. (2006), demonstrating both the presence of a location-based CSPC Stroop effect, and the absence of a shape-based CSPC Stroop effect. The null result of Experiment 1b is particularly important. Although the prior failure to observe shape-specific CSPC Stroop effects could have been attributed to participants lack of awareness of a contingency between shape and proportion congruent, the same cannot be said here. A shape-based CSPC effect was not observed even when participants were told explicitly about the shape-specific proportion congruent manipulation, as well as encouraged to use shape-specific proportion congruent strategies to enhance efficiency of performance. This finding demonstrates that awareness of the CSPC manipulation is not sufficient to produce CSPC Stroop effects.

3. Experiment 2: The role of task relevance

The results of Experiments 1a and 1b further substantiated the claim that CSPC Stroop effects do not depend on awareness of the proportion congruent manipulation. Instead, CSPC Stroop effects appear to be mediated by learning that is implicit in nature. If the CSPC Stroop effect is mediated by implicit learning processes, then principles that are well-established in that literature may also help to explain why CSPC Stroop effects were obtained using location cues but not shape cues to proportion congruent. We pursued this possibility in Experiment 2.

Jimenez and Mendez (1999) demonstrated that implicit learning of associations between shape cues and upcoming responses in a serial reaction time (SRT) task depended on the extent to which processing of the shape dimension was made task-relevant. Specifically, they demonstrated that learning about the shape dimension occurred when participants were asked to keep a running count of particular shapes encountered during the task. Similarly, the influence of the shape dimension on performance disappeared when the participants were no longer required to keep a running count of different shapes. The results of Jimenez and Mendez support the principle that implicit learning does not depend on awareness of the to-be-learned task structure, but instead depends on selective attention to the to-be-learned task structure (Frensch & Runger, 2003).

The purpose of Experiment 2 was to investigate whether the implicit learning principle described by Jimenez and Mendez (1999) would generalize beyond the scope of sequence learning tasks, and help explain why CSPC Stroop effects have been observed using location cues but not shape cues to proportion congruent. In particular, Crump et al. (2006) argued that the presence of CSPC effects using location cues to proportion congruent fits well with the notion that location information receives priority during encoding (Mayr, 1996; Logan, 1998). On this view, although the location of a target stimulus is nominally irrelevant to the color-naming task, target-localization may be inherent to identifying other attributes of a stimulus such as color. As a result, subordinate task demands inherent to the location-based CSPC manipulation necessitate selectively attending to location information, and thereby support learning of the location-specific proportion congruent manipulation. In contrast, the shape of a target stimulus may be both nominally and functionally irrelevant to the color-naming task. As a result, the lack of a shape-based CSPC effect could be explained by failures to selectively attend to the shape dimension of the target stimulus. We tested this hypothesis in Experiment 2 by modifying Experiment 1b so that processing of the shape dimension became task-relevant. We followed Jimenez and Mendez (1999) and modified Experiment 1b so that participants were required to keep a running count of the number of squares that were encountered while performing the Stroop task. Our prediction was that selective processing of the shape dimension would support learning of the shape-specific proportion congruent manipulation.

3.1. Methods

3.1.1. Participants

The participants were 35 undergraduate students enrolled in psychology courses at McMaster University who volunteered for course credit. All participants spoke English as a first language, had normal color vision, and had normal or corrected to normal visual acuity.

3.1.2. Materials and procedure

This experiment was conducted by 15 trained student experimenters in partial fulfillment of a psychology lab course at McMaster University. Each experimenter tested one participant in Experiment 2. The remaining participants were tested by the first author and a research assistant. Experiment 2 followed the same procedure as Experiment 1b with two exceptions. First, participants were told nothing about the shape-based proportion congruent manipulation. Second, a shape counting task was introduced. On each trial, participants were instructed to name the color of the color-patch probe as quickly and accurately as possible. They were further instructed to count silently the number of squares that appeared during the course of the experiment. Participants were told that they would be asked to report the number of squares that they had counted at the end of each block of trials. At the beginning of each block participants were told to start counting squares beginning from zero.

3.2. Results

Five participants in Experiment 2 were excluded from all following analyses. Four of these participants were excluded due to microphone failure. The remaining participant was excluded because their mean RT was more than three standard deviations from the group mean. For the remaining 30 participants, correct RTs greater than 100 ms for each condition were submitted to an outlier elimination procedure (Van Selst & Jolicoeur, 1994). Mean RTs were computed using the remaining observations and then submitted to a 2 (proportion congruent: high vs low) by 2 (congruency: congruent vs. incongruent) repeated measures ANOVA. RTs and error rates for each condition, collapsed across participants, are displayed in Table 3.

The main effect of congruency was significant [$F(1, 29) = 90.19$, $MSE = 2058.53$, $p < .0001$]. Responses for congruent trials (558 ms) were faster than responses for incongruent trials (637 ms). More important, the proportion congruent by congruency interaction was significant [$F(1, 29) = 9.3$, $MSE = 322.20$, $p < .005$]. The Stroop effect for the high proportion condition was larger (89 ms) than the Stroop effect for the low proportion condition (69 ms). A corresponding analysis of error rates revealed only a main effect of congruency [$F(1, 29) = 17.8$, $MSE = 7.32 \times 10^{-4}$, $p < .0005$]; error rates were higher for incongruent trials (.020) than for congruent trials (.003). The counting estimates given by each participant for each block indicated that they were performing the counting task with considerable accuracy (actual number of squares = 48, mean estimate of number of squares = 43, $SE = 0.70$).

3.3. Discussion

Experiment 2 was the first demonstration that CSPC Stroop effects can be observed using shape cues to proportion congruent, and that CSPC Stroop effects can be mediated by contextual information other than stimulus location. Critically, the shape-based CSPC effect was observed when task demands required selective processing of the shape dimension. This finding extends the principle that implicit learning depends on

Table 3
Mean correct color-naming response latencies (in ms), with standard errors (in parentheses), and error rates for Experiment 2

Proportion		Item type		I–C	CSPC effect
Congruent		Congruent (C)	Incongruent (I)		
High	RT	556	645	89	
	SE	(12)	(15)	(10)	
	ER	.004	.03		
Low	RT	560	628	69	20
	SE	(12)	(13)	(8)	(7)
	ER	.002	.02		

CSPC, context specific proportion congruent; RT, response time; SE, standard error; ER, error rate.

selective attention (Jimenez & Mendez, 1999), and suggests that selective attention is required to support learning of the association between different contexts and proportion congruent.

The results of Experiment 2 are worth considering from the perspective of Melara and Algom (2003) tectonic theory of Stroop effects, which distinguishes between two important processes, dimensional imbalance and dimensional uncertainty. Dimensional imbalance refers to differences in the relative salience between target and distractor dimensions. Dimensional uncertainty refers to the extent to which target and distractor dimensions are correlated. Melara and Algom argue that highly salient and informative dimensions draw attentional resources and guide performance. Generally speaking, this information theoretic approach fits well the notion developed here that participants will process and learn about incidental contextual cues when they are salient and/or informative.

Although Tectonic theory does not explicitly deal with processing of nominally irrelevant contextual information, which is the focus of the current set of experiments, the principles of dimensional imbalance and uncertainty can apply broadly to provide insight into the finding that CSPC Stroop effects emerge for some contextual dimensions but not others. For example, in Experiments 1a and 1b, the presence of a location-based CSPC Stroop effect, but absence of a shape-based CSPC Stroop effect, could reflect the interplay between dimensional imbalance and uncertainty. That is, correlations between target, distractor, and context dimensions were held constant across location (Experiment 1a) and shape dimensions (Experiment 2a), so it appears that processing of the contextual information in Experiments 1a and 1b was largely driven by differences in the relative salience of the contextual information, rather than differences in dimensional uncertainty.

It is also noteworthy that a shape-based CSPC effect was obtained in Experiment 2 without changing either the relative salience or the informativeness of the contextual cue. This finding suggests that the contribution of dimensional uncertainty is modulated not only by relative salience of the contextual cue, but also by task-related constraints that direct attention to selectively process the context dimension.

4. Experiments 3a and 3b: The role of relative salience

Melara and Algom (2003) notions of dimensional imbalance and dimensional uncertainty provide a theoretically motivated set of principles for understanding boundary conditions for observing CSPC Stroop. In particular, the presence of the CSPC Stroop effect may reflect the interplay between dimensional imbalance and uncertainty. That is, processing of highly salient and highly informative contextual dimensions should encourage the presence of CSPC Stroop effects. At the same time, changes to the relative salience or informativeness of the context dimension should constrain the presence of CSPC Stroop effects. The purpose of Experiments 3a and 3b was to directly evaluate the role of dimensional imbalance in constraining the influence of the CSPC manipulation.

Experiment 3a was a replication of the location-based CSPC Stroop task reported by Crump et al., (Exp 2a, 2006). Experiment 3b followed the same general procedure as Experiment 3a, except that the prime and probe stimuli were reversed. Participants in Experiment 3b were presented with a color-patch prime at fixation followed by a color-word (in white) that appeared above or below fixation. Across both experiments, the context-specific proportion congruent manipulation was applied to the location context of the probe item. We were interested in determining whether the CSPC effect would survive a task-reversal manipulation which is well known to reduce or eliminate the Stroop effect. That is, we were interested in determining whether changes to the relative salience of the target and context dimensions would constrain the extent to which participants were influenced by the same contextual cue.

4.1. Methods

4.1.1. Participants

The 30 participants in Experiment 3a, and 30 participants in Experiment 3b were undergraduate students enrolled in psychology courses at McMaster University who volunteered for course credit. All participants spoke English as a first language, had normal color vision, and had normal or corrected to normal visual acuity.

4.1.2. Materials and procedure

Experiment 3a followed the same procedure used in Experiment 1a except that participants were not informed of the CSPC manipulation Experiment 3b was the reverse of Experiment 3a, and involved the presentation of a color-patch prime, followed by a color-word probe display. The task in Experiment 3b was to ignore the color-patch prime, and name aloud the color-word probe. All properties of the prime and probe except for their order of presentation were held constant.

4.2. Results

For all participants in each experiment, RTs greater than 100 ms from correct trials for each condition were submitted to an outlier elimination procedure (Van Selst & Jolicoeur, 1994). Mean RTs were then computed using the remaining observations. The results from both experiments were submitted to a 2 (proportion congruent: high vs low) by 2 (congruency: congruent vs. incongruent) repeated measures ANOVA. RTs and error rates for each condition, collapsed across participants in each experiment, are displayed in Table 4.

4.2.1. Experiment 3a: Name color

There was a significant main effect of congruency [$F(1, 29) = 131.72$, $MSE = 2846.92$, $p < .0001$]. Responses for congruent trials were faster (484 ms) than responses for incongruent trials (595 ms). More important, the proportion congruent by congruency interaction was significant [$F(1, 29) = 6.74$, $MSE = 225.70$, $p < .05$]. The Stroop effect for the high proportion location condition was larger (119 ms) than

Table 4
Mean correct color-naming response latencies (in ms), with standard errors (in parentheses), and error rates for Experiments 3a (Name color) and 3b (Name Word)

Experiment	Proportion Congruent		Item type: Congruent (C)	Item type: Incongruent (I)	I–C	CSPC effect
3a	High	RT	480	598	119	
		SE	(9)	(16)	(9)	
		ER	.01	.04		
	Low	RT	488	592	105	14
		SE	(10)	(17)	(11)	(5)
		ER	.01	.04		
3b	High	RT	458	468	10	
		SE	(9)	(8)	(3)	
		ER	.002	.01		
	Low	RT	463	474	11	−1
		SE	(8)	(8)	(3)	(5)
		ER	.002	.01		

CSPC, context specific proportion congruent; RT, response time; SE, standard error; ER, error rate.

the Stroop effect for the low proportion location condition (105 ms). A corresponding analysis of error rates revealed only a main effect of congruency [$F(1, 29) = 30.77$, $MSE = 1.07 \times 10^{-3}$, $p < .0001$]; error rates were higher for incongruent trials (.04) than for congruent trials (.01).

4.2.2. Experiment 3b: Name word

There was a significant main effect of congruency [$F(1, 29) = 6.65$, $MSE = 140.99$, $p < .05$]. Responses for congruent trials were faster (461 ms) than responses for incongruent trials (471 ms). Interestingly, there was no significant proportion congruent by congruency interaction. A corresponding analysis of error rates revealed only a main effect of congruency [$F(1, 29) = 5.94$, $MSE = 8.76 \times 10^{-5}$, $p < .05$]; error rates were higher for incongruent trials (.01) than for congruent trials (.002).

4.2.3. Combined RT analysis

To determine whether the CSPC Stroop effect in Experiment 3a was significantly larger than the CSPC Stroop effect in Experiment 3b, a mixed-design ANOVA with experiment (Name color vs. Name word) as a between-participant factor was conducted. The three-way interaction between experiment, proportion congruent and congruency was significant [$F(1, 58) = 4.34$, $MSE = 189.21$, $p < .05$].

4.3. Discussion

The results of Experiment 3a (name color) demonstrated a location-based CSPC Stroop effect and replicated the pattern of results reported by Crump et al., (2006, Exp 2a). In contrast, a location-based CSPC Stroop effect was not observed in Experiment 3b (name word). Experiments 3a and 3b establish that dimensional imbalance, or the relative salience of target, distractor, and context dimensions, contrains the extent to which contextual cues guide performance. These results closely mirror the results of Dishon-Berkovits and Algom (2000), Experiments 4 and 5 who demonstrated that learning about correlations between a distractor dimension and a target dimension can be obscured when the target dimension is more salient than the distractor dimension. In our case, Experiment 3b establishes similar boundary conditions for learning (or expression of learning) about correlations between contextual cues and likelihood of congruency. Specifically, the location-based CSPC Stroop effect was not observed when the target dimension was a highly salient word.

5. General discussion

The purpose of the present experiments was to clarify the role of awareness, task-relevance, and dimensional imbalance in producing CSPC Stroop effects. Experiments 1a and 1b demonstrate that awareness of the CSPC manipulation was not sufficient to produce shape-based CSPC Stroop effects. Experiment 2 demonstrates that shape-based CSPC Stroop effects can be observed when task constraints require processing of the shape dimension. Experiments 3a and 3b demonstrate that changes to the relative salience of target, distractor, and context dimensions can prevent learning about the CSPC manipulation from influencing performance. The following discussion evaluates candidate explanations of the CSPC Stroop effect, and discusses the implications of each explanation for theories of cognitive control.

Conventionally, psychologists have distinguished between automatic processes that capture attentional resources involuntarily and controlled processes that direct attentional resources voluntarily (Posner & Snyder, 1975; Shiffrin & Schneider, 1977). By this view, strategic control serves as an alternative basis for selectively encoding and responding to the environment when automatic processing of salient stimulus properties in that environment would lead selection mechanisms astray. In a Stroop color-word context, for example, the preparation of an encoding strategy prior to stimulus onset might help to offset the potentially interfering influence of the salient word dimension. In contrast to this conventional view, the CSPC Stroop effects reported here (see also Crump et al., 2006; Jacoby et al., 2003) appear to reveal a form of control over the salient word dimension that is rapid and involuntary, rather than slow and strategic. However, prior to accepting the idea that CSPC effects implicate rapid, involuntary control over word reading in a Stroop context, other competing theoretical accounts merit consideration.

5.1. The event frequency hypothesis

Crump et al. (2006) discussed the possibility that CSPC Stroop effects reflect a learning process sensitive to differences in event frequency. For example, in the high proportion congruent context, particular congruent word/context/color events are experienced with high frequency, whereas particular incongruent word/context/color events are experienced with low frequency (see Table 1). As a result, the large Stroop effect for items appearing in the high proportion congruent context could reflect asymmetries in learning about high and low frequency events (Logan, 1988). An explanation of this nature would not require any inferences about rapid, involuntary control, and therefore ought to be given serious consideration. There are several forms of evidence that suggest that different event frequencies on their own fall short of fully accounting for the CSPC effect.

First, the results of Experiment 3b failed to show a CSPC Stroop effect despite employing the same asymmetries in event frequency used in Experiment 3a. This result demonstrates that differences in event frequency are not sufficient to produce a CSPC effect, and that instead some form of interaction between stimulus salience (or dimensional imbalance) and proportion congruent (or dimensional uncertainty) lies at the heart of the learning that produces the CSPC effect.

Second, if event frequency learning follows a power law learning principle, then any contribution of event frequency to the CSPC effects ought to dissipate with increasing amounts of experience with those events. The rationale for this prediction is that, although power law learning should reach asymptotic levels earlier for the most frequent event types (e.g., congruent trials in the high proportion congruent condition, and incongruent trials in the low proportion congruent condition), any consequent differences in performance for frequent and infrequent item types should eventually disappear when performance in all conditions approaches asymptote. In other words, one might expect differences in event frequency to produce a CSPC effect at some point in learning, but such an effect ought to diminish with extended practice. In fact, there was no evidence that CSPC effects dissipated with increasing experience in the present study [2]. Further, in a separate study that measured CSPC effects in a global-local task across ten experimental sessions, the CSPC effect was remarkably consistent across training (Milliken, Leboe, & Leboe, 2003). At present, then, we have no evidence to suggest that the CSPC effect is an emergent outcome of power law learning for events of different frequency.

Third, we have taken a more direct approach to addressing the event frequency hypothesis in a separate line of study. The key to this approach is to ask whether a CSPC Stroop effect can be observed for a set of events that have been experienced with equal frequency. A question of this nature can be addressed by creating distinct subsets of Stroop items, which we refer to as context and transfer items. The context items might be Stroop items made using red/green color-word combinations, whereas transfer items might be Stroop items made using yellow/blue color-word combinations. Importantly, the CSPC manipulation is applied only to the context items. For example, context items appearing above fixation could be 100% congruent, whereas context items appearing below fixation could be 100% incongruent. In contrast, congruent and incongruent transfer items appear with equal frequency in both locations, but mixed randomly within blocks with the context items. The critical issue is whether the Stroop effect for the transfer items is modulated by the context in which they appear. Indeed, several pilot results indicate reliable CSPC Stroop effects for the transfer items despite the fact that the congruent and incongruent transfer items appear with equal frequency in both the high and low proportion congruent location contexts.

In summary, several lines of evidence suggest that CSPC Stroop effects are not entirely driven by a learning process that is sensitive to differences in event frequency. Ruling out the event frequency hypothesis gives license to a discussion of the possible links between CSPC effects and cognitive control.

5.2. The involuntary control hypothesis

Botvinick et al. (2001) point out that an important problem in research into cognitive control processes is to understand how selection weights are modified without invoking the operation of a goal-driven homunculus.

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[2] The CSPC effects from all experiments in this article were submitted to a 3 (Experiments: 1a, 2, and 3a) × 4 (block: 1, 2, 3, and 4) mixed design ANOVA. Neither of the main effects nor the interaction were significant. This analysis suggests that the CSPC Stroop emerges early in practice, and does not diminish as a result of practice. A similar result was obtained by Jacoby et al. (2003).

Toward this end, Botvinick et al.'s (2001) propose that shifts in cognitive control may be driven by an involuntary mechanism that monitors for conflict. This process evaluates conflict during performance of a trial, then sends a signal to trigger appropriate adjustments to task demand weights that are carried forward to guide selective attention on the next trial. The conflict monitoring hypothesis accounts for trial-to-trial shifts in performance as seen in sequential effects (Gratton, Coles, & Donchin, 1992), performance after errors (Laming, 1968), and block-wide shifts in performance as seen in proportion congruent modulations to the Stroop effect (Tzelgov, Henik, & Berger, 1992). Taken together, the conflict monitoring hypothesis takes an important step in the direction of understanding how selective attention control settings may be adjusted by involuntary means.

An important property of the conflict monitoring hypothesis is that adjustments to task demand weights are made at one point in time, and carry forward to influence performance at a later point in time. In contrast, the CSPC Stroop effect reported here appears to reflect adjustments to control settings made rapidly, at the time of target onset. This inference stems from the CSPC manipulation, which prevents participants from knowing whether an item belongs to the high proportion congruent or low proportion congruent condition until its onset. In other words, carry-over of control settings from a previous trial to a current trial fails to explain the CSPC effect (see Crump et al., 2006). Instead, if the CSPC Stroop effect reflects changes to selective attention control settings, then contextual cues must provide a signal that can be used rapidly to change those settings. In its current form, Botvinick et al.'s (2001) conflict monitoring module does not receive input from episodic memory. It would be interesting to see whether adding an episodic input to the conflict monitoring module would produce the rapid control adjustments required to explain the context-specific control effects reported here.

At the same time it may be unnecessary to suppose that episodic processes and conflict monitoring processes are inherently linked. For example, an alternative approach is that episodic processes contribute directly to adjustments of control settings. Crump et al. (2006) proposed an episodic account of the CSPC Stroop effect, and we elaborate on that account here. Our episodic approach borrows from recent episodic accounts of implicit learning phenomena (Brooks & Vokey, 1991; Whittlesea & Dorken, 1993; for a review see, Neal & Hesketh, 1997). On this view, implicit learning is not a qualitatively different kind of learning, rather implicit learning phenomena reflect an indirect route to accessing the same episodic representations that support both explicit and implicit learning phenomena (Whittlsea & Dorken, 1997). On the one hand, our view is similar to Logan (1988), in that we assume storage of instances of performance in memory, and that retrieval of these instances supports online performance. We also follow Jacoby and Brooks (1984); Kolers and Roediger (1984) in assuming that episodes of performance stored in memory represent many aspects of the performance episode. Specifically, we assume that episodes of performance represent not only stimulus–response information, but also incidental contextual information, and perhaps even episode-specific selective attention procedures for filtering task-relevant from task-irrelevant information. To clarify this last point, we assume that episodic representations can include the selective attention control settings used during encoding of particular episodes.

To further specify our notion that selective attention procedures are encoded as part of memory episodes, we note a distinction made by Kolers and Smythe (1984) between allographic and autographic representations. Allographic representations refer to the kind of abstract, amodal, analytic symbols that are well-articulated, trans-situational, and easily copiable (e.g., binary operators). Autographic representations refer to symbols that are uncopiable, extremely dense, and not well-articulated (e.g., think of a painting as being a symbol of itself). We argue that the implications of instance theory for online performance depend on whether the instance representation is thought of allographically, or autographically. In our view, it is important to recognize that memory instances are autographic, and represent the rich and subtle complexities of experience. To connect these ideas with our discussion of cognitive control processes, we assume that memory instances are autographic, and include representations of the control procedures mediating selection at the time of encoding. In this way, we argue that the retrieval of item/context-specific control procedures stored in memory can serve as potent sources for control over online performance. Memory-driven influences over performance do not necessarily reflect the inflexible contribution of automatic routines; rather, because the routines incorporate aspects of previously employed control procedures, the routines themselves can provide flexible control over selection during online performance.

As a final point of clarification, the crux of this discussion is not whether an episodic approach outstrips the conflict monitoring hypothesis. Rather, we wish to point out that episodic processes are likely to contribute to the control of attention, and that this contribution could well be distinct from that of conflict monitoring processes.

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