Journal of Experimental Psychology: General
2003, Vol. 132, No. 3, 400–418

0096-3445/03/$12.00 DOI: 10.1037/0096-3445.132.3.400

Modulation of Word-Reading Processes in Task Switching

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The authors examined modulation of the simple act of word naming induced by the conflict arising when that task competes with color naming in a task-switching paradigm. Subjects alternated between naming a word printed in black and naming the color of a stimulus in 2 conditions. In the incongruent condition, the colored stimulus was an irrelevant word generating conflict, and in the neutral condition, color was carried by a row of asterisks. Subjects took substantially longer to name a word printed in black in the incongruent condition, implying a form of suppression. This modulation of the word-naming response was adaptive in that it led to more efficient color naming. The modulation effect was replicated using phoneme detection instead of word naming but not with lexical decision or visual comparison, implicating a phonological encoding process.

Responding to stimuli that invite the application of different, competing processes requires specialized control mechanisms to resolve conflict. For example, naming the color of a written word entails avoiding the habitual tendency to read the word, and subjects are substantially slower to name colors under this condition compared with a condition in which they are required to name the color of a neutral stimulus, such as a row of *X*s (e.g., Klein, 1964). This type of conflict is particularly prevalent in situations where subjects rapidly switch from one task to another and the stimulus on each trial affords both the currently demanded task and the previously executed one (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 2000; Meiran, Chorev, & Sapir, 2000). Switching between tasks under these circumstances undoubtedly involves a form of executive control operating through a central executive or a supervisory attentional system (Baddeley, Chincotta, & Adlam, 2001; Logan & Gordon, 2001; Norman & Shallice, 1986). In addition, however, there is a need to consider the consequences of resolving the conflict that is generated when a stimulus has attributes relevant to the two currently active task sets between which the subject is switching. For example, resolving the conflict inherent in the act of naming the color in which a word is printed may lead to the suppression of word-reading processes, which may then have consequences on a subsequent trial when word reading is demanded. In this article, we examine the idea that this form of suppression may constitute an essential component of the cost associated with switching between tasks.

Task-switching costs arise when subjects are required to shift between at least two different tasks on a sequence of trials and are particularly apparent when each target stimulus is bivalent; namely, it invites the application of either of the two tasks. In comparison to performance on a series of trials involving a single task, performance in trials that are part of a sequence of two alternating tasks is significantly worse (e.g., Allport et al., 1994; Jersild, 1927; Spector & Biederman, 1976). The cost of switching between tasks can be reduced but not eliminated by allowing subjects substantial time (on the order of seconds) to prepare for an upcoming task switch (e.g., Meiran, 1996; Rogers & Monsell, 1995). The reduction in switch cost achieved by providing subjects with preparation time is generally accepted as evidence for executive control processes. But the residual switch cost—the cost remaining after adequate preparatory time is granted—is a component of switch cost that is the target of some controversy.

In one view, even the residual switch cost is ascribed to an aspect of executive control, whereby a new task cannot be fully engaged until it is externally cued by a task-relevant stimulus (Rogers & Monsell, 1995). A rival account of residual switch cost is that disengagement of a completed task invokes inhibition of that task set to enable the switch to a new task (Mayr & Keele, 2000). This *backward inhibition* makes it more difficult to return to the inhibited task set when required by a subsequent task switch. Yet another account is that switch cost is the result of the combined effects of (a) inadvertent and inappropriate cuing of the

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This research was supported by research grants from the Natural Sciences and Engineering Research Council of Canada to Michael E. J. Masson and to Daniel N. Bub. Order of authorship for the first two authors is arbitrary. Thanks are extended to Seth Bloom, Shaina Hood, Erica McCollum, Camelia Pakzad-Vaezi, Neil Pegram, and Lucas Riedl for assistance with data collection. We also thank Iring Koch, Ulrich Mayr, and Nachshon Meiran for helpful comments on an earlier version of this article.

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previous task by the current stimulus and (b) suppression of an irrelevant task on trial N that now becomes relevant on trial $N + 1$ (Allport et al., 1994; Allport & Wylie, 2000).

The controversy regarding how best to interpret residual switch costs is not yet resolved. Our goal is not to adjudicate between different accounts of residual switch costs but to explore the general idea that suppression arising from conflict between two operations invited by a bivalent stimulus is an important component of switch costs. Conflict of this nature can arise when a bivalent stimulus consists of two arbitrarily coupled dimensions, each affording a different response. For example, in the Rogers and Monsell (1995) experiments, a bivalent stimulus consisted of a digit–letter compound, and subjects were cued to respond to one or the other element on a given trial. In this case, conflict arises when the irrelevant task set is active by virtue of having been performed recently and is cued by an aspect of the stimulus display. Conflict can also occur when one element of a bivalent stimulus inherently evokes a habitual response that is incompatible with the desired response to the other element of the stimulus. The Stroop color-naming task is a classic example of this situation. Here, the strong tendency to identify a written word invariably interferes with the task set of naming the color in which an incongruent color word is presented.

For both of these potential sources of conflict, we suggest that processing operations associated with the irrelevant task evoked by a bivalent stimulus are suppressed in the course of responding to the cued task (see also Allport & Wylie, 2000). If the previously irrelevant stimulus aspect is then cued to produce a task switch on a subsequent trial, suppression on trial N of the operations required for the task on trial $N + 1$ will lead to slower responding. Suppression occurring as part of task-conflict resolution when responding to a bivalent stimulus is distinct from the concept of backward inhibition developed by Mayr and Keele (2000). Recall that backward inhibition is invoked by the requirement to engage in a task switch and is applied to a task after it is performed. In contrast, the suppression mechanism that we consider is applied to processes associated with the irrelevant task and arises because of the need to resolve the conflict that occurs when two tasks compete and only one is to be performed. This competition and ensuing suppression may be especially likely to occur if one task is more habitual than the other and the subject is required to perform the less habitual or nondominant task (e.g., naming the color of a printed word). In a study consistent with this idea, Allport et al. (1994) reported asymmetrical switch costs, finding larger costs when subjects switched from color naming to word naming than vice versa.

To examine the contribution of suppression independent of other components of switch costs, we constructed a situation in which a stimulus (e.g., a word printed in color) affords two possible, competing tasks, only one of which is to be executed. Conflict is particularly strong if the word refers to a color, but substantial conflict also occurs even when words do not refer to colors (Burt, 2002; Klein, 1964; Monsell, Taylor, & Murphy, 2001). We assume that to resolve such task competition, some aspect or aspects of the nonselected task must be suppressed, particularly if that task is the more habitual or dominant one. Therefore, first, one stimulus in a sequence of trials could be a word printed in color, where the task is to name the color. In this situation, we assume that subjects would tend to suppress some process involved in the competing, habitual task of word naming. Second, the next task performed after a task switch would be the one that was avoided (and that we assume was suppressed) before the switch. Moreover, because we are interested in directly measuring suppressive effects, we wish to avoid a situation in which the previous task set (color naming) would be evoked by the current stimulus. Therefore, the stimulus following the bivalent item must not contain an element relevant to the previous task. Thus, after being presented with a colored word for color naming, subjects must name a word presented in black, when black is not among the colors used on color-naming trials. We assume that this constraint on the word-naming stimulus reduces the possibility that a color-naming response will be cued by the word. Accordingly, any impact on word reading is unlikely to be the outcome of conflict induced by the stimulus cuing the previous task set of color naming.

We arranged color-naming and word-naming tasks as follows. Each trial consisted of two events (see Figure 1). In the first event, a word printed in black was presented for the task of naming aloud. This event was immediately followed by a second event consisting of a colored stimulus presented for the task of naming the color. In conditions in which suppression was to be evoked, the color stimulus was a word. In our experiments, words were never the names of colors, nor were they strongly associated with color concepts. Nevertheless, to produce a color-naming response, subjects would have to overcome competition from the potential response to the word carrying the color (Burt, 2002; Klein, 1964;

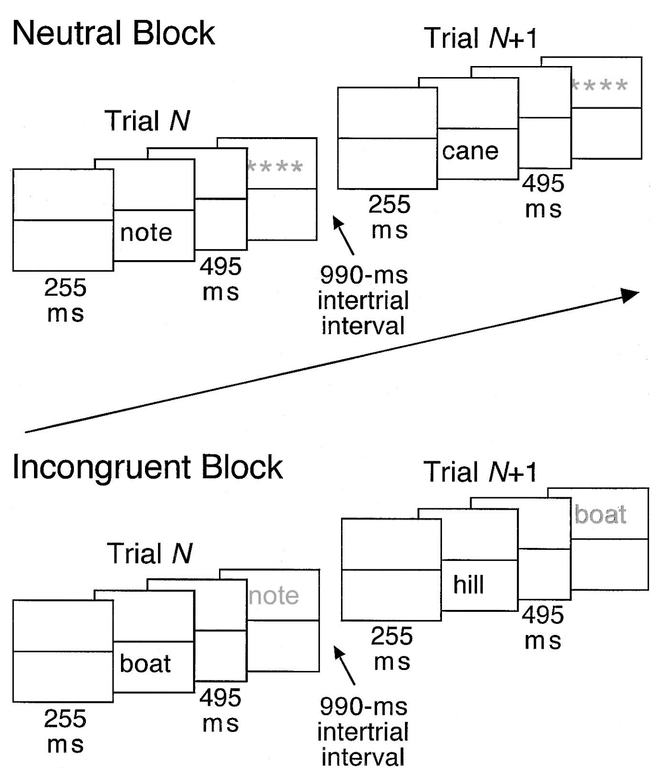

Figure 1. Illustration of events for two trials in neutral and incongruent trial blocks. Stimuli appearing in gray actually were presented in one of five colors.

Monsell et al., 2001). We assume that the resolution of this competition is the source of the suppression that we wish to investigate. A relatively long pause after the color-naming response and before the start of the next trial was used, allowing the subject to prepare for the next trial. Any preparatory processes involved as part of executive control over task performance should have had ample time to be carried out before the arrival of the word-naming stimulus on the next trial. By having the word-reading event occur first in each trial, we are in a position to examine the suppressive effect of color naming on subsequent word reading, after a substantial interval.

In addition, we eliminated aspects of residual switch costs that are unrelated to suppression in the following way. In one block of trials, referred to as the *incongruent block*, color-naming stimuli consisted of a word printed in color. On these trials, it is assumed that word-naming processes are suppressed. Thus, each trial began with a word-naming event (a word printed in black) and ended with a color-naming event (a word printed in color). In another block of trials, referred to as the *neutral block*, color-naming stimuli consisted of a row of uniformly colored asterisks. On these trials, the first event was again word naming (a word printed in black) and the second event was again color naming (a row of colored asterisks). An example of each type of trial is shown in Figure 1.

The critical comparison we make is between word-naming response times in the incongruent block and word-naming response times in the neutral block. This comparison is taken as a relatively pure assessment of the influence of suppression (occurring on trial N) on subsequent word reading (occurring on trial $N + 1$). To reiterate, both the neutral and the incongruent blocks include a substantial delay between color-naming and word-naming events, allowing ample time for preparation, and we are comparing word-naming response times under two conditions, which both require a switch from color naming to word naming. However, word reading in the incongruent block occurred after the resolution of a conflict occasioned by naming the color in which an unrelated word was printed. In the neutral block, word naming occurred in the absence of conflict.

Our approach contrasts with other methods of examining the effects of switching in alternating tasks. These methods involve either (a) comparing a pure block of a single task with a block of trials involving the same task alternating with another task (the *pure–alternating block method*) or (b) alternating runs in which at least two different tasks are carried out, with each task repeated a number of times before a switch (the *alternating-runs method*). When comparing pure blocks of trials, evidence for a switch cost consists of less efficient task performance in the alternating block. There is a disadvantage to the pure–alternating block method in that only in the alternating block do subjects have to maintain two task sets in working memory (Fagot, 1994). An advantage to using the alternating-runs method is that both task sets must be maintained when subjects perform switch and nonswitch trials. The measure of switch cost in this case is provided by a comparison between performance on the first trial after a switch with performance on subsequent nonswitch trials.

For both the pure–alternating block method and the alternating-runs method, however, there remains the potential influence of at least one factor that is not directly associated with switching between tasks. In particular, we suggest that whenever a bivalent stimulus is used and conflict resolution is required to make a selective response, task-switch effects include enduring consequences of this resolution. If conflict resolution leads to the suppression of processing operations that must then be invoked after a task switch (Allport & Wylie, 2000), then switch costs will include the cost of overcoming this suppression.

Our method allows us to directly examine the impact of suppression on task performance that can be assessed independent of switch costs. The critical comparison is between performance in blocks of trials where switching occurs between two univalent stimuli (neutral block) and performance in blocks of trials where switching occurs between a univalent stimulus and a bivalent stimulus (incongruent block). Both blocks, then, require a task switch on every trial (word naming followed by color naming). The crucial difference between the neutral and incongruent blocks is the use of a bivalent stimulus (a colored word) in the color-naming task. We assume that in the incongruent block, color naming of a bivalent stimulus requires conflict resolution leading to the suppression of word naming. If this suppression carries over to the next word-naming event, then we expect to see slower word naming than in the neutral block (where color naming involves a univalent stimulus).

Suppression may have an item-specific component as well as a more general influence operating at the level of a particular task. For example, Allport and Wylie (2000) examined word-reading performance on color words that had served as stimuli in a prior Stroop color-naming task (i.e., color words printed in a conflicting color). They also examined word-reading performance on additional color words that subjects had never encountered as Stroop stimuli. Interference relative to a baseline condition was observed for both sets of words, although a larger effect was found for words that had appeared in the Stroop task. These results suggest that suppression, if it exists, is not confined only to the words that actually were present as competitors during color naming. Of course, given that only color words were used throughout, it is possible that these general effects are due to priming between conceptually related items (a form of semantic interference; see, e.g., Yee, 1991).

One of our goals with the research reported here was to determine whether task suppression that may result from conflict in Stroop-like situations applies to specific items or generalizes across item types. Suppression of word-reading processes during a color-naming task may generalize beyond the words that actually appear in the color-naming task and beyond items conceptually related to those words. It is well known that interference in color naming can occur even when color is carried by words that are not themselves related to color concepts (Dalrymple-Alford, 1972; Fox, Schor, & Steinman, 1971; Klein, 1964; Monsell et al., 2001). Therefore, it should be possible to observe effects on word naming even when the words do not refer to color and are unrelated to those colors presented on the color-naming task.

In addition, we consider another fundamental question raised by the notion of task suppression: Does suppression apply to entire task sets (Gilbert & Shallice, 2002) or to specific component processes (Meiran et al., 2000)? In the case of switching from naming a color to naming a word, researchers typically have been satisfied to construe competition as occurring between whole task sets (e.g., the task set for color naming and the task set for word naming). The tendency to theorize at the level of whole tasks rather than the level of component processes has been criticized before. Jacoby (1991) argued against the use of direct and indirect tests of memory as a means of examining conscious and unconscious influences because tasks cannot be assumed to be process pure. He developed an alternative approach based not on dissociations between tasks but on dissociations between component processes. Neuropsychology and modern aphasiology have benefited considerably in the last few decades from the insistent admonishment by cognitive scientists that the effects of brain damage on functional systems cannot be adequately described in terms of global tasks like reading or color naming. Given such prior awareness of the limits inherent in the attempt to understand cognitive organization using global tasks, it is ironic that many current attempts to specify the nature of switch costs can be faulted for the same emphasis on tasks rather than cognitive processes as the conflicting elements.

The question of item specificity is addressed in Experiment 1 by the use of either (a) a small set of repeatedly presented words that appeared both in color-naming and in word-naming events or (b) a large set of words, none of which were ever repeated. Because we use unrelated noncolor words in the large, unrepeated set, we cannot ascribe any effects obtained on word naming to item-specific suppression or priming among related items. Rather, such effects would be due to suppression of either the general task of word naming or some specific processing mechanism. To address the issue of process specificity, we also examined suppression effects on tasks other than word naming. One task involved visual comparison of nonlinguistic characters, and this allowed us to determine whether suppression generated by the color-naming task applies generally to the encoding of visual forms and/or to the production of a response to a stimulus. An alternative possibility is that suppression affects a specific stage in the process of encoding an orthographic stimulus into a phonological or an articulatory code. If the locus of suppression is at a relatively early stage, such as orthographic encoding, then any word-reading task should show suppression.

Alternatively, the suppression may affect some later stage of encoding involving the construction of a phonological code, in which case suppression effects would not be seen in word-reading tasks that can be executed without relying on a phonological code. The lexical-decision task is a candidate for this purpose given that Hino and Lupker (2000) and Waters and Seidenberg (1985) found that the effect of orthographic regularity, whereby regular words (e.g., *hint*) are named more quickly than irregular words (e.g., *pint*), does not occur in the lexical-decision task. In the Waters and Seidenberg study, this restriction was obtained when subjects were required to respond under deadline conditions, although Hino and Lupker obtained this result even when a deadline was not imposed. For our purposes, however, it is sufficient to assume that the lexical-decision task can be performed without relying on a phonological code that is developed to the point of articulation. We draw a distinction between this form of phonological encoding, which is necessary for explicit naming, and earlier phonological representations that are constructed moments after the visual presentation of a word (e.g., Lukatela & Turvey, 1994; Perfetti & Bell, 1991; Rayner, Sereno, Lesch, & Pollatsek, 1995). Thus, the hypothesis that we test in contrasting word naming with lexical decision is that suppression specifically affects the construction of a phonological code for naming.

Experiments 1–2: Generality and Source of Word-Naming Modulation

Experiments 1A and 1B

In one version of Experiment 1, we used a small set of noncolor words, each appearing repeatedly both in the word-naming task and in the color-naming task. The reason for using a small set of items was that we did not initially know whether the suppression effect arising from the color-naming task would be confined to specific items seen in that task (Allport et al., 1994; Allport & Wylie, 2000). If so, then using a small set of items would be necessary for any effect to emerge. In the other version of Experiment 1, we tested the hypothesis that suppression applies to a general processing mechanism independent of the specific items used.

Method

Subjects. The subjects in Experiment 1A were 12 undergraduate students at the University of Victoria who received extra credit in an introductory psychology course for their participation in the experiment. All subjects who participated in the experiments reported here were drawn from this pool. No subject participated in more than one experiment. For Experiment 1B, 24 subjects were tested.

Materials. Five 4-letter words were selected for the critical and practice trials of Experiment 1A. The words ranged in frequency from 12 to 127 occurrences per million (Kučera & Francis, 1967), with a median of 72. The words selected had no particular association with color concepts. For Experiment 1B, a critical set of 180 words was selected. The words ranged from 4 to 7 letters in length, were one or two syllables, and ranged in frequency of occurrence from 0 to 143 per million, with a median of 42. Again, the words had no particular association with color concepts. The critical words were arranged as six lists of 30 words. Assignment of these lists of words to conditions in the experiment was counterbalanced across subjects so that no word was seen more than once by a particular subject and each word was seen equally often in each condition. Three of the six lists were used for each subject. An additional set of 30 words with characteristics similar to those of the critical words was selected for use as practice items.

Procedure. Subjects in Experiment 1A were tested individually in a quiet room using a Macintosh desktop computer with a color monitor. A voice-activated relay was connected to the computer keyboard. Subjects were presented with two blocks of 10 practice and 30 critical trials, with each trial requiring the performance of two different tasks. One block was the neutral condition and the other was the incongruent condition. The order in which these blocks were presented was counterbalanced across subjects. For both blocks of trials, the first task on each trial involved naming aloud as quickly as possible a word printed in black. For the block of neutral trials, the second task on each trial involved naming aloud the color in which a row of five asterisks was presented. For the block of incongruent trials, the second task involved naming aloud the color in which a word was presented. For these two color-naming tasks, there were five different colors, each used with equal frequency: blue, green, pink, red, and yellow. With respect to critical trials, each word was presented six times in the word-naming task in the neutral block, six times in the word-naming task in the incongruent block, and six times in the color-naming task in the incongruent block. Trials in the incongruent block were arranged so that no word appeared both for word naming and for color naming on the same trial. For the practice trials, each of the words was presented two times for word naming in each block and two times for color naming in the incongruent block.

At the start of each block, subjects were informed that they would be performing two different tasks on each trial and that the two tasks would always be performed in the same order. The nature of the two tasks involved in each block of trials was explained, and subjects were instructed to respond as quickly and as accurately as possible. Each block began with 10 practice trials, followed by 30 critical trials.

Each trial began with the presentation of a vertically oriented rectangle at the center of the computer monitor. The rectangle subtended a visual angle of 22.6° vertically and 19.0° horizontally when viewed from 40 cm. The rectangle was divided into equal-sized upper and lower boxes by a horizontal line. The rectangle was in view for 255 ms, then a word was presented in lowercase black letters in the center of the lower box. Stimuli presented for both tasks were printed in 36-point Geneva font. A five-character item subtended a horizontal visual angle of 5.0°. The word remained in view until it was named by the subject, then it was erased. After a 495-ms pause, the colored stimulus for the second task was presented in the center of the upper box and remained in view until the subject named its color. The experimenter pressed a key on the keyboard to record whether an error or a voice-activated relay failure had occurred on either task. The colored item and the rectangle were then erased, and there was a pause of 990 ms before the next trial began automatically. A brief rest was given at the end of the first block of trials and before the instructions for the second block were given.

The same procedure as in Experiment 1A was used for Experiment 1B, except that no word was presented to a subject more than once. To meet this constraint, one of the three lists of 30 critical words seen by each subject was used for the word-naming task in the neutral block of trials, another was used for the word-naming task in the incongruent block, and the third was used for the color-naming trials in the incongruent block.

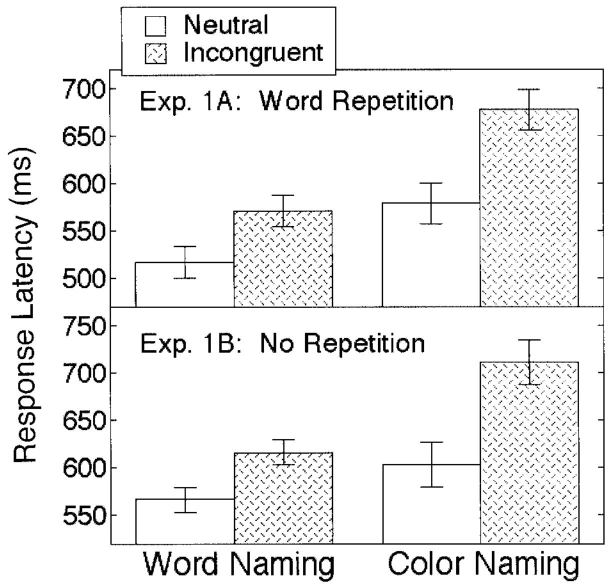

Figure 2. Mean response latency on the word-naming and color-naming tasks in Experiments 1A (word repetition) and 1B (no repetition) as a function of block type. Exp. = Experiment. Error bars show 95% within-subject confidence intervals (Loftus & Masson, 1994).

Results and Discussion

Response latencies less than 100 ms or greater than 3,000 ms were excluded from consideration. Boundaries for exclusion of response latencies were set in this and in subsequent experiments so that no more than 0.5% of responses were excluded (Ulrich & Miller, 1994). No responses on the word-naming task were excluded on this basis. For the color-naming task, 1 response in Experiment 1A (0.1%) and 2 in Experiment 1B (0.1%) were excluded from the analysis.

For each subject, mean response latencies on trials with correct responses were computed for word-naming and color-naming tasks in each of the two blocks of trials. For each of the experiments reported here that involved separate blocks of neutral and incongruent trials, we adopted the following procedure for data analysis. First, the subject latency means and error percentages for each task were submitted to analyses of variance (ANOVAs) with order of block as an independent variable. If no effects involving order of block were significant, an ANOVA collapsing across that variable was computed and the results of that analysis are reported. If effects of order were obtained, the results of the ANOVA including that variable are reported. A Type I error rate of .05 was used in all analyses reported here.

The mean response latency for each task in Experiment 1A is shown in the upper panel of Figure 2 as a function of block type. The data for Experiment 1B are in the lower panel of Figure 2. No effects of block order were found for either task in either version of the experiment, so the means shown in Figure 2 are collapsed across that variable. For the color-naming task, the effect of block type was significant in Experiment 1A, $F(1, 11) = 50.38$, $MSE = 1{,}163$, with longer response latencies in the incongruent block. The color-naming task, then, produced an interference effect, in which responding was slowed when color was carried by a word rather than by a row of asterisks. The effect found here is similar to that reported by Dalrymple-Alford (1972) and Monsell et al. (2001) for color naming of words unrelated to color concepts versus color naming of rows of *X*s or other unpronounceable character strings. In Experiment 1B, an interference effect of similar magnitude was found, $F(1, 23) = 44.34$, $MSE = 3{,}149$.

However, our primary theoretical interest lies in the results involving the word-naming task. In Experiment 1A, the effect of block type on word naming was significant, $F(1, 11) = 24.72$, $MSE = 706$, whereby word-naming latencies were longer in the incongruent block than in the neutral block. This outcome represents a clear interference effect on the first task (word naming) as a function of the demands of the second task (color naming of words vs. asterisks) performed on each trial. In Experiment 1B, a similar interference effect was found, $F(1, 23) = 29.56$, $MSE = 986$.

To determine whether the interference effect in the word-naming task depends on using a small number of repeatedly presented words (Experiment 1A) or a large set of words presented only once each (Experiment 1B), we analyzed the word-naming data from these two experiments in a single ANOVA. Experiment and block type were the independent variables. This analysis revealed a main effect of experiment, with shorter response latencies in Experiment 1A than in Experiment 1B (545 ms vs. 592 ms), $F(1, 34) = 4.63$, $MSE = 7{,}706$. The latency advantage for Experiment 1 most likely is due to the benefits of repeated presentation commonly seen in the word-naming task (e.g., MacLeod & Masson, 2000; Scarborough, Cortese, & Scarborough, 1977). There was also a reliable interference effect, $F(1, 34) = 47.58$, $MSE = 895$, that did not interact with experiment, $F < 1$. Thus, the interference effect was of comparable magnitude, regardless of whether a small number of words were presented repeatedly (54 ms) or a large number of words were presented once each (49 ms).

In Experiment 1A, only 3 errors or voice-activated relay failures were made in the word-naming task and only 2 such events occurred in the color-naming task, so no analysis of these data was carried out for either task. An analysis of mean error percentage in Experiment 1B found no effects, *F*s < 1.3, and the overall mean error percentage, including trials spoiled because of inappropriate or failed triggering of the voice-activated relay, was 2.0%. Only 2 subjects made word-naming errors in Experiment 1B (1 error each), so no analysis of errors in this task was carried out.

The results of Experiment 1 revealed a clear interference effect on the first task (word naming) as a function of the demands of the second task (color naming of words vs. asterisks) performed on each trial. This modulation of performance of the first task occurred even when target words were never repeated, suggesting that the effect is not dependent on item-specific influences. We do not wish to imply that a suitable arrangement of events (e.g., the same word appearing for color naming then reappearing as the next word-naming stimulus, or the use of color words as the stimuli) would not reveal an item-specific component to the suppression effect we have obtained. Our point is that even when no possibility exists for item specificity, we see clear evidence for modulation of word naming as result of naming the color of a printed word.

Experiment 2

We have assumed that the source of the modulation of word naming seen in Experiment 1 is a form of suppression carryover from the previous color-naming event. An alternative explanation for the modulation of word naming is that it is a preparatory process (perhaps a form of advance suppression) made in anticipation of the upcoming color-naming event. We can distinguish between these possibilities by presenting two consecutive stimuli on each task in an alternating-runs procedure (Rogers & Monsell, 1995). We continued with the task arrangement in which the first task on each trial was word naming and the second task was color naming. For color naming, two different color stimuli were presented in succession; for word naming, two different words were presented in succession. Each of the stimuli was to be named aloud. This arrangement would allow us to determine whether the influence of naming the color of words as opposed to asterisks differentially affects naming of the first versus the second noncolored word. If naming the first noncolored word takes substantially less time than does naming the second one, then the modulation of word naming can be ascribed to the effect of color naming on the previous trial. This outcome would be expected if the act of successfully naming the first word reduces the modulation effect caused by the immediately preceding color-naming event. If, on the other hand, it is the second noncolored word that is named in a time that is substantially slower than the time needed to name the first, we would conclude that the modulation of word naming is an anticipatory process. This alternative outcome would be expected if anticipatory preparation is applied to the stimulus that is temporally closest to the upcoming color-naming event.

In Experiment 2, we used a longer interval (3 s) between successive trials, where a trial consisted of the presentation of two word stimuli followed by two color stimuli. The reason for this increase was to allow ample time for preparatory processes to be completed before the onset of the first word stimulus of a trial. Although we have no systematic evidence that this interval is sufficient to completely eliminate preparatory influences, we note that Allport and Wylie (2000) used intervals of between 1 and 2 s for this purpose and deemed that to be an adequate range for preparing to switch between word- and color-naming tasks.

Method

Subjects. Thirty-six subjects were tested in Experiment 2.

Materials. A set of 10 four-letter critical words was selected. Each word had a frequency of 20 occurrences per million. The same five colors as in Experiments 1A and 1B were used.

Procedure. The testing session began with a practice phase of 20 word-naming trials, in which each of the 10 critical words was presented twice. In the task-switching phase, two successive stimuli were presented for each task (i.e., two words to be named, then two colors to be named). Both word-naming items appeared below a row of equal signs and both color-naming stimuli appeared above (see explanation below). Word stimuli for each trial were sampled from the pool of 10 words so that no word appeared more than once on a given trial. Two different colors were used for the two color stimuli presented on each trial.

The display used for Experiment 2 was modified from that used in Experiment 1. Rather than using a box to define the spatial location of stimuli, we had a row of five equal signs presented in the center of the computer monitor at the start of each trial. Word-naming items appeared one line below this marker, and color-naming items appeared one line above it. All stimuli were displayed in 12-point bold Courier font. A five-character word subtended a horizontal visual angle of 2.4° when viewed from 40 cm, and the vertical distance between the lower bound of the word-naming stimuli and the upper bound of the color-naming stimuli was 1.9°. We also changed the timing of the presentation of stimuli. Each task-switching trial began with a 495-ms presentation of the row of equal signs, followed by the appearance of a word printed in black below that marker. The subject named the word, which was then erased. There was a 750-ms pause between the offset of the first word and the onset of the next word. After the two words had been presented, the experimenter made two key presses to classify the correctness of the responses to the two word-naming stimuli. This procedure required approximately 500 to 1,000 ms and varied in duration from trial to trial. Then the color-naming stimuli appeared, were responded to, and were erased in the same manner. The experimenter made two key presses to classify the correctness of the color-naming responses. The delay between trials (i.e., the time between the last of the two color-naming stimuli of one trial and the first word-naming stimulus of the next trial) was approximately 3 s. The neutral and incongruent blocks each began with 20 practice trials and were followed by 40 critical trials.

Results and Discussion

Response latencies outside the range of 100 ms to 3,000 ms in either the word-naming or the color-naming task were excluded from analysis (0.5% and 0.2% of responses, respectively). An additional 0.9% of word-naming responses and 0.9% of color-naming responses were excluded because of failed or inappropriate triggering of the voice-activated relay.

The mean response latencies in the word-naming task as a function of stimulus (first vs. second) and block (neutral vs. incongruent) are shown in the upper panel of Figure 3. Block order had no effect, so the data were collapsed across this variable. A Type I error rate of .05 was used in all analyses. An ANOVA indicated that response latencies were reliably longer for the first of the two stimuli, $F(1, 35) = 47.73$, $MSE = 1{,}409$, and longer in the incongruent block than in the neutral block, $F(1, 35) = 34.37$,

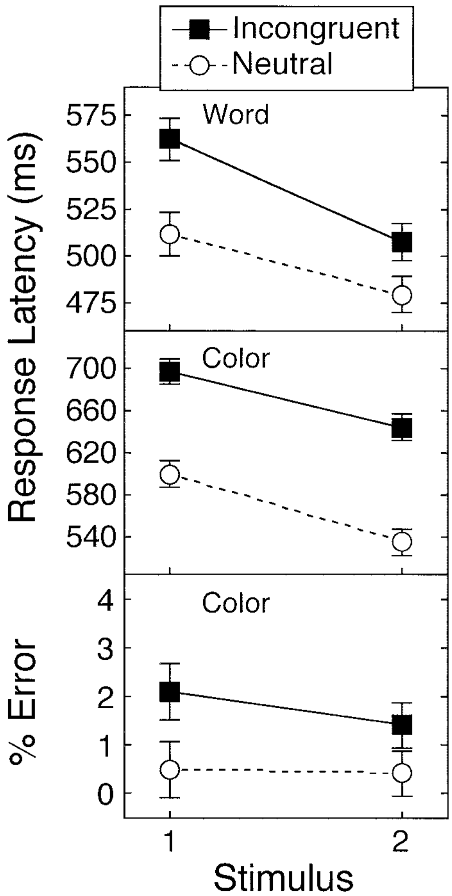

Figure 3. Mean response latency on the word-naming task and mean response latency and mean percentage of error on the color-naming task in Experiment 2 as a function of block type and stimulus. Two stimuli were shown in succession for each task. Error bars show 95% within-subject confidence intervals and are appropriate for assessing block-type and stimulus effects.

MSE = 1,618. In addition, there was a reliable interaction between these two variables, $F(1, 35) = 12.38$, *MSE* = 363. As Figure 3 indicates, the effect of block was nearly twice as large on the first word-naming stimulus as on the second stimulus. Clearly, then, the interfering influence of words for color naming exerted itself primarily on the first of the two word-naming stimuli. In addition, when only the data for the neutral block were considered, response latencies were reliably longer on the first stimulus than on the second stimulus, $F(1, 35) = 21.18$, *MSE* = 873, indicating that there was a residual switch cost of 32 ms on the word-naming task, even when a neutral stimulus carried the color on the color-naming task. There were only 7 errors in the word-naming task, so no statistical analysis of error data was conducted.

Color-naming performance was not affected by block order, so the mean response latency and percentage of error data shown in Figure 3 (middle and lower panels, respectively) were collapsed across that variable. An ANOVA of the color-naming latencies revealed a significant effect of block, $F(1, 35) = 200.65$, *MSE* = 1,881, replicating the interference effect seen in the earlier experiments. In addition, response latencies were longer on the first stimulus than on the second stimulus, $F(1, 35) = 145.40$, *MSE* = 841. These two factors did not interact, $F < 1.4$, so the longer response latency on the first stimulus indicates that there was a significant switch cost that was independent of the nature of the colored stimulus. An ANOVA of the percentage of error revealed only a significant effect of block, with more errors in the incongruent block than in the neutral block, $F(1, 35) = 20.27$, *MSE* = 3.00.

The results of Experiment 2 provide strong evidence to support the hypothesis that the modulation of word naming induced by the requirement to name the color in which a preceding word appears is due to the carryover of a form of suppression from the color-naming task. Had this modulation effect been due to an anticipatory process whereby subjects prepared themselves for the upcoming color-naming task by modulating word reading, we would have expected to see a larger modulation effect on the second of the two word-naming stimuli. Instead, the reverse result was obtained, showing that the first of the two word-naming stimuli—which was temporally closer to the preceding color-naming event—bore the brunt of the modulation effect. It appears, then, that the modulation is stimulated by the previous color-naming episode and that subjects, to some degree, overcome that carryover effect in the course of naming the first of the two word stimuli in the word-naming task.

Experiments 3–4: Accrual of Adaptive Control

Experiment 3

To this point, we have relied on blocked runs of incongruent or neutral trials. The modulation of word naming that we have observed may occur immediately after a single color-naming episode in which word naming must be avoided, or it may depend on a learning process that accrues over multiple episodes. Varying approaches to task switching instantiate both of these possibilities to different degrees. Some researchers use runs of trials in which subjects perform the same task then a switch to a competing task (e.g., Allport & Wylie, 2000; Rogers & Monsell, 1995). Others have used the method of alternating tasks, in which two competing tasks are performed consecutively, and they contrast that condition with one in which tasks are performed in pure blocks (e.g., Allport et al., 1994; Jersild, 1927). If the modulation we have observed is invoked after a single encounter in which a color carried by a word must be named, then it may contribute to switch cost in both of these types of task-switching paradigms.

In Experiment 3, we investigated the possibility that modulation of word naming is instantiated by a single color-naming episode. To do this, we presented single neutral trials (in which subjects were to name a word, then name the color carried by asterisks) and incongruent trials (in which subjects were to name a word, then name the color carried by another word) in an alternating sequence. With this arrangement, we expected that suppression arising from color naming of a word stimulus would be generated during the color-naming event on an incongruent trial, then expressed on the word-naming event of the subsequent neutral trial. Thus, a suppression effect would be indicated by longer word-naming response times on neutral trials, relative to incongruent trials—the opposite of what was seen in Experiments 1 and 2. This pattern is expected because the slowing of word naming was shown in Experiment 2 to be a carryover effect from the color-naming task on the preceding trial. By alternating single incongruent and neutral trials in Experiment 3, we created a situation in which the source of suppression (color naming of a word) occurs just before the word-naming event in a neutral trial.

Whatever modulating effects on word naming occurred after a color-naming event would not be the result of general switch costs, because every word-naming event constituted a switch from color naming. Rather, modulation effects would be the consequence of the suppression of word naming on incongruent trials that took place just prior to the task switch.

Method

Subjects. Eighteen subjects were tested.

Materials. A set of 120 critical words was selected. These words ranged in length from four to six letters and in frequency from 47 to 660 (*Mdn* = 105) occurrences per million. The critical words were arranged into three lists of 40 items each for counterbalanced assignment of lists to conditions. Two lists were assigned for use on the incongruent trials (one for the word-naming task and one for the color-naming task), and one list was assigned to the neutral trials (for the word-naming task). A similar set of 60 words was selected for use on practice trials. The five colors from the earlier experiments were used.

Procedure. The procedure was similar to that of Experiment 1, except that rather than presenting neutral and incongruent trials in separate blocks, these trials were presented in an alternating sequence. Half of the subjects began with a neutral trial (in which they read a word printed in black, then named a color presented by a row of asterisks) that was then followed by an incongruent trial (in which they named a word printed in black, then named a color carried by a word), whereas the other half of the subjects began the sequence of alternating trials with an incongruent trial. The display layout conformed to the layout of Experiment 2. Each task-switching trial began with a 495-ms presentation of the row of equal signs, followed by the appearance of a word printed in black below that marker. As soon as the subject named the word, it was erased. After a pause of 450 ms, the color-naming stimulus appeared above the marker. The subject named the color, then both the marker and the color-naming stimulus were erased. The experimenter then made two key presses to classify the subject's responses on the word- and color-naming trials. The monitor remained blank for an additional 2.5 s after those key presses, then the next trial began automatically.

Subjects first completed 40 practice trials consisting of 20 neutral and 20 incongruent trials in alternating sequence. Eighty critical trials followed in which 40 neutral and 40 incongruent trials alternated.

Results and Discussion

Response latencies outside the range of 100 ms to 1,000 ms in the word-naming task or outside the range of 100 to 3,500 ms in the color-naming task were excluded from analysis (0.1% and 0.4% of responses, respectively). Failed or inappropriate triggering of the voice-activated relay led to the exclusion of an additional 0.5% of word-naming responses and 0.6% of color-naming responses.

Mean response latencies in the word-naming and color-naming tasks are presented in Figure 4. A Type I error rate of .05 was used in all analyses. For the color-naming task, response latencies were reliably longer on incongruent trials than on neutral trials, $F(1, 17) = 103.54$, $MSE = 707$. There was also an interference effect in the error percentage for the color-naming task, with more errors on incongruent trials (1.6% vs. 0.3%), $F(1, 17) = 7.36$,

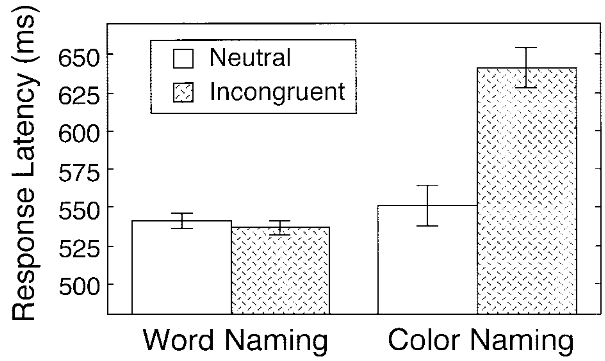

Figure 4. Mean response latency on the word-naming and color-naming tasks in Experiment 3 as a function of trial type (neutral vs. incongruent). Error bars show 95% within-subject confidence intervals and are appropriate for assessing trial-type effects.

$MSE = 1.25$. In the word-naming task, however, there was no effect of trial type on either the latency measure, $F(1, 17) = 1.98$, $MSE = 90$, or the error measure, $F < 1$. Mean error percentages were 0.3% and 0.4% on the neutral and incongruent trials, respectively.

Single alternation of neutral and incongruent trials yielded no reliable difference between these two trial types on the word-naming task. This null result stands in marked contrast to the large interference effect on word naming obtained in Experiments 1A, 1B, and 2 when neutral and incongruent trials were presented in separate blocks. There are two possible explanations for this difference in outcomes. First, the alternation between single neutral and incongruent trials may have prevented the accrual of modulation of word naming. In this account, the modulation of word naming requires a form of learning over a series of successive incongruent trials, where the color stimulus is a word. The alternative possibility is that the modulation effect is established after just a single occasion of naming the color of a word, but it does not dissipate over the course of the following neutral trial, where color is carried by a row of asterisks. Thus the influence of modulation would be present on every trial in Experiment 3 and would not be detectable.

Experiment 4

To obtain stronger evidence on the question of whether modulation of word naming accrues over multiple color-naming episodes, we conducted a further experiment in which subjects performed alternating runs of 2 neutral trials and 2 incongruent trials or alternating runs of 10 neutral trials and 10 incongruent trials. By comparison, Experiments 1 and 2, which showed strong modulation of word naming, presented a single block of 40 or 60 neutral or incongruent trials (including practice and critical trials). If modulation is absent after only a single incongruent trial, as implied by Experiment 3, and accumulates gradually over a consecutive sequence of color-naming episodes, we would expect a small modulation effect in word naming with runs of just 2 trials and a much larger effect for runs of 10 trials. In both cases, however, word naming in the neutral trials should approach pre-interference levels after some number of trials.

In addition to addressing the question of accrual of modulation, this experiment allowed us to study three fundamental issues regarding the nature of this modulation and its potential adaptive significance in resolving the conflict experienced when responding to a bivalent stimulus. First, assuming that modulation is learned, it is possible that what is established is a mode of responding that can be fully reinstantiated when cued by a single bivalent stimulus event. In that case, once the modulation effect has been formed (e.g., after the first run of 10 incongruent trials), it should reemerge almost full-blown after the first trial of the subsequent run of incongruent trials. Alternatively, the modulation may have to be relearned gradually at the beginning of each run of incongruent trials. Second, on the assumption that modulation dissipates over the course of a series of neutral trials, we can ask whether that dissipation occurs slowly or immediately after a single trial. Finally, we inquire into the adaptive significance of modulation. If the modulation of word naming plays a causal role in reducing the interference experienced during color naming of a bivalent stimulus, then when modulation of word naming is instantiated, so should interference in color naming diminish.

Method

Subjects. Thirty-six subjects were tested. By random assignment, 12 subjects were in the runs-2 condition and 24 were in the runs-10 condition. A larger number of subjects were tested in the runs-10 condition because we were interested in tracking performance across trials within a run. To obtain an adequate number of observations at each trial position within a run, we needed more subjects in the runs-10 condition.

Materials. The critical items were 300 words that were four or five letters in length, ranging in frequency from 6 to 967 occurrences per million (*Mdn* = 40). An additional set of 30 words was created for practice trials. The five colors from the earlier experiments were used. Assignment of critical words to neutral and incongruent trials and to word-naming or color-naming tasks was random. Each critical word was presented exactly once to each subject.

Procedure. The procedure was similar to that of Experiment 3, except that the alternating sequence of neutral and incongruent trials consisted of runs of 2 trials of each trial type for one group of subjects (runs-2 condition) and runs of 10 trials of each type for the other group (runs-10 condition). A run of 2 or 10 trials of one type (e.g., incongruent trials) was followed by an equally long run of trials of the other type (e.g., neutral trials). Half of the subjects in each run condition began with a run of neutral trials, and the other half of the subjects began with a run of incongruent trials. Trial events were the same as in Experiment 3. For subjects in the runs-2 condition, the first 5 runs of each trial type were treated as practice trials, and for subjects in the runs-10 condition, the initial run of each trial type was treated as practice. Thus, each group of subjects was provided with 10 practice trials of each type. After the practice trials, 200 critical trials were presented. For the runs-2 condition, the critical trials consisted of 50 alternating runs of 2 incongruent and 2 neutral trials. For the runs-10 condition, the critical trials were presented as 10 alternating runs of 10 incongruent and 10 neutral trials.

Results and Discussion

Response latencies outside the range of 100 ms to 2,000 ms on the word-naming task and those outside the range of 100 ms to 3,500 ms on the color-naming task were excluded from analysis. This constraint resulted in the removal of 0.2% and 0.3% of word-naming and color-naming observations, respectively. A further 3.1% and 3.7% of word- and color-naming trials, respectively, were excluded because of artifactual or failed triggering of the voice-activated relay. A Type I error rate of .05 was used in all analyses.

Error rates in the word-naming task were very low, averaging 0.2% across subjects, and did not significantly vary as a function of either run condition (2 vs. 10) or trial type (neutral vs. incongruent). In the color-naming task, error rates did not vary across run condition, but there were reliably more errors in the incongruent condition than in the neutral condition (3.0% vs. 0.3%), $F(1, 34) = 35.49$, $MSE = 3.39$.

Our analyses of response latency data were conducted separately for the runs-2 and the runs-10 conditions and emphasized the modulation of latency both across trials within a run and between trial types. Mean response latencies for each run condition are shown in Figure 5. For the runs-2 condition, color-naming performance was analyzed in an ANOVA with trial position within a run (1 vs. 2) and trial type (neutral vs. incongruent) as the independent variables. The only significant effect in this analysis was trial type, $F(1, 11) = 71.87$, $MSE = 1{,}525$, indicating that color-naming responses were significantly faster in the neutral condition.

A comparable ANOVA applied to word-naming latencies in the runs-2 condition revealed no main effects, but a there was a significant interaction between trial position within a run and trial type, $F(1, 11) = 12.34$, $MSE = 139$. Figure 5 shows that the source

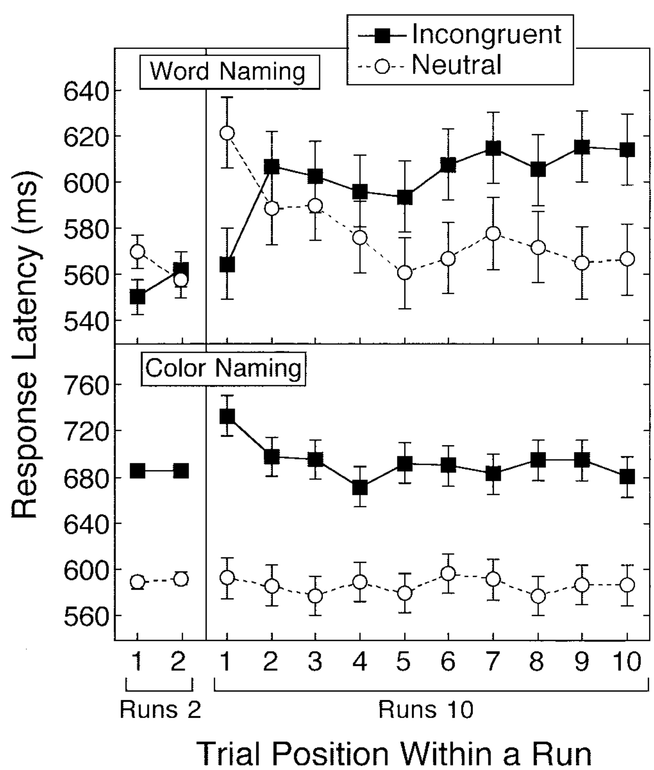

Figure 5. Mean response latency on the word-naming and color-naming tasks in Experiment 4 as a function of block type and trial within a run. Error bars show 95% within-subject confidence intervals and are appropriate for assessing block-type and trial effects. Error bars for the color-naming task in the runs-2 condition are smaller than the symbols.

of this interaction was a slowing of naming responses on the first trial of a run of neutral trials (which would have followed a run of two incongruent trials), relative to response latency on the first trial of a run of incongruent trials (which would have followed a run of two neutral trials), and an elimination of this difference on the second trial of a run. This first-trial difference of 19 ms is much smaller than the 50-ms modulation of word naming seen in the earlier experiments. Nevertheless, it is reliable and larger than the nonsignificant effect seen in Experiment 3, where single neutral and incongruent trials alternated. Thus, at least part of the modulation effect was able to develop even when subjects were given just two consecutive trials of each type.

Moreover, naming latency quickly changed in response to the color-naming stimulus on the first trial of a run. After that color-naming event, the second word-naming stimulus in an incongruent run evoked a slower response, relative to the first trial, whereas in a neutral run, the second word-naming stimulus got a response more quickly than did the first. This pattern suggests that subjects invoked a small modulation of word naming after the first color-naming stimulus in an incongruent run, and they quickly began to release that modulation after receiving the first set of colored asterisks in a neutral run. The fact that modulation occurred in the aftermath of a color-naming event supports the conclusion drawn from the results of Experiment 2 that modulation is a carryover effect generated by conflict in a color-naming task rather than an anticipatory response.

The results from the runs-10 condition yielded a pattern that was similar in some key respects to that seen in the runs-2 condition, although the effect sizes were much larger. In the case of word naming, an ANOVA with trial position within a run and trial type as the independent variables found a significant effect of trial type, $F(1, 23) = 36.55$, $MSE = 1{,}820$, with slower responding on incongruent trials. It is important to note that the trial-type effect was reversed for the first trial position, whereby naming latency was longer in the neutral run than in the incongruent run. As in the case of the runs-2 condition, then, the first naming response after a run of incongruent trials (which started a run of neutral trials) was slower than the first naming response after a run of neutral trials (which started a run of incongruent trials). For the runs-10 condition, this effect was 56 ms—quite similar to that seen when incongruent and neutral trials were fully blocked. The changing patterns of word-naming latencies across trials within neutral versus incongruent runs generated a significant interaction, as was the case in the runs-2 condition, $F(9, 207) = 7.76$, $MSE = 1{,}469$. Figure 5 shows that by the second trial in a run, much of the change in naming latency had already taken place. That is, modulation was quickly invoked in an incongruent run and quickly dissipated in a neutral run.

The difference in the magnitude of the word-naming modulation seen in the runs-2 versus runs-10 conditions might, as we suggest, be due to differences in the degree to which subjects can learn to modulate word naming under these two conditions. Alternatively, subjects might have learned modulation equally well in both conditions but strategically deployed this modulation to different extents. In the runs-2 condition, the frequent occurrence of task switching might have led subjects to avoid complete instantiation of modulation because they were aware that the task would change soon. Assuming that invoking modulation is effortful, this strategic avoidance would be reasonable. However, the runs-10 data show that modulation can be invoked immediately after the first color-naming response in the incongruent condition and terminated after the first encounter with a color-naming stimulus in the neutral condition. Given the immediacy of these changes, applying and terminating modulation may not be sufficiently effortful to motivate deliberate, strategic avoidance. Moreover, as we show below, a cost is associated with such a strategy with respect to color-naming performance.

The color-naming data for the runs-10 condition provide a further important fact. Figure 5 shows that in the incongruent runs, color naming on the initial trial was much slower than on later trials. An ANOVA found a significant effect of trial type, with much slower responding on incongruent trials, $F(1, 23) = 164.72$, $MSE = 8{,}306$. In addition, there was a significant effect of trial position within a run, $F(9, 207) = 2.15$, $MSE = 1{,}788$, and the interaction between trial type and trial position approached significance, $F(9, 207) = 1.91$, $MSE = 1{,}819$, $p = .052$. There clearly was no variation in color-naming latency across trials within neutral runs, $F < 1$, but there was a significant reduction in latency across trials in incongruent runs, $F(9, 207) = 2.49$, $MSE = 2{,}524$, with much of that reduction occurring between the first and second trial of a run. Thus, the onset of word-naming modulation after the first trial of an incongruent run closely coincided with a reduction in color-naming latency.

No such reduction in color-naming latency was observed in the runs-2 condition, indicating that the degree of word-naming modulation applied there was insufficient to benefit color naming. This outcome reduces the appeal of the idea that subjects strategically avoided complete modulation of word naming in the runs-2 condition, as discussed above. Avoiding complete modulation would entail forfeiting a substantial benefit in color naming that is clearly evident in the runs-10 condition. Thus, our preferred interpretation of the difference in the amount of modulation of word naming observed in the runs-10 versus runs-2 condition is that the ability to modulate requires a relatively long sequence of incongruent trials to develop.

One goal of Experiment 4 was to determine whether the absence of modulation observed in Experiment 3 reflected a failure of learning or the lack of dissipation of modulation across alternating neutral and incongruent trials. The results of Experiment 4 provide an unambiguous answer to this question, namely, modulation is learned over the course of as many as 10 consecutive incongruent trials but is weakly present even when only 2 consecutive incongruent trials are run. Therefore, it is not the case that the failure to observe modulation in Experiment 3 reflects persistence of modulation across incongruent and neutral trials; instead, it was due to the lack of sufficient opportunity for modulation to accrue.

Having shown that the initial learning of modulation requires a series of consecutive trials, the question becomes whether the reinstatement of modulation after dissipation induced by a series of neutral trials is similarly a gradual process or can be effected immediately after a single incongruent trial. It is clear from Figure 5, particularly from the runs-10 data, that once modulation has been established, presumably by the initial practice run or shortly thereafter, it is immediately reinvoked after just one trial of naming a color carried by a word. As for dissipation of modulation, it is equally clear that word naming returns to nearly normal speed within a very few neutral trials after a run of incongruent trials. In addition, it can be seen that color naming in incongruent trials benefits directly from modulation of word naming. As word-naming latency increases on incongruent trials, so does color-naming latency decrease in a contingent fashion. Therefore, we have strong evidence of an adaptive, causal relationship between the modulation of word naming and the relative efficiency of color naming under conditions of word–color interference. We note that the features of this dynamic relationship include rapid reinstantiation of learned modulation and rapid recovery to baseline performance when modulation is no longer required. This pattern represents a remarkably adaptive solution to the problem of conflict resolution when cognitive processes are in competition.

Experiments 5–7: Process Specificity of Modulation

Experiment 5

The first four experiments established three important facts regarding the modulation effect that were revealed by our task-switching paradigm. First, the effect is not due to repetition of items and therefore is a general one that affects some processing mechanism. Second, the modulation is not an anticipatory effect but a carryover from prior color naming when the color stimulus was a word. Third, modulation accrues over trials of the incongruent type and quickly dissipates when a run of neutral trials is encountered; it is also quickly reinvoked once a new run of incongruent trials begins. The next three experiments were designed to allow us to examine the question of the nature of the word-processing mechanism involved in the modulation effect. In Experiment 5, we tested the hypothesis that visual encoding processes in general are affected rather than some process specific to word reading. Therefore, we examined whether modulation was present even in a task requiring visual comparison of unfamiliar characters that have no associated verbal label.

Method

Subjects. Sixteen subjects were tested.

Materials. A set of 8 pseudo-Chinese characters were created for use in a visual-comparison task, and a set of 60 words was constructed for use in the color-naming task. The normative frequency of these words ranged from 5 to 109 occurrences per million, with a median frequency of 35.

Procedure. The same procedure as Experiment 1 was used, with the following exceptions. First, the display characteristics were the same as in Experiments 2–4. Second, the testing session began with 30 practice trials of the visual-comparison task. On each trial, two pseudo-Chinese characters appeared side by side, below the string of equal signs, until the subject pressed one of two keys on a response box to indicate whether the characters were the same or different. Two characters subtended a horizontal visual angle of 2.0° and a vertical visual angle of 0.9° when viewed from 40 cm. For task-switching trials in the neutral and incongruent blocks, the visual-comparison task replaced the word-naming task. Words used in the color-naming task in the incongruent block were randomly assigned to either the practice trials or the critical trials. For the practice trials in the visual-comparison task and for each block of task-switching trials, the two displayed characters were identical on half the trials and different on the other half. Across the two blocks of task-switching trials, 6 of the identical character pairs appeared eight times each and the other 2 identical pairs appeared six times each. Of the 56 possible different pairs (taking into account left–right position of each character), 52 appeared once each and the remaining 4 appeared twice each.

Results and Discussion

Response latencies in the visual-comparison task and in the color-naming task that were outside the range of 100 ms to 2,000 ms were excluded (0.3% for both tasks). A further 0.8% of color-naming responses were lost due to voice-activated relay failures. A Type I error rate of .05 was used in all analyses.

Mean latencies for correct responses on the color-naming task are shown in the lower panel of Figure 6. The data for subjects who received the neutral block first and for subjects who received the incongruent block first are presented separately because the block-order variable influenced color-naming times. As the figure illustrates, mean response latency was reliably longer in the incongruent block, $F(1, 14) = 102.79$, $MSE = 385$, but this effect was stronger when the neutral block was presented first, producing a Block Type × Block Order interaction, $F(1, 14) = 6.91$, $MSE = 385$. The main effect of block type is consistent with the results from the earlier experiments, but it is unclear why the effect was modulated by block order. One way of interpreting the interaction is to note that subjects generally were slower on the second of the two blocks of trials they received, regardless of whether it was the neutral block or the incongruent block. It is not clear why this effect arose in this experiment, as it did not appear in any other experiment reported here. Only 1 error was made by 1 subject in

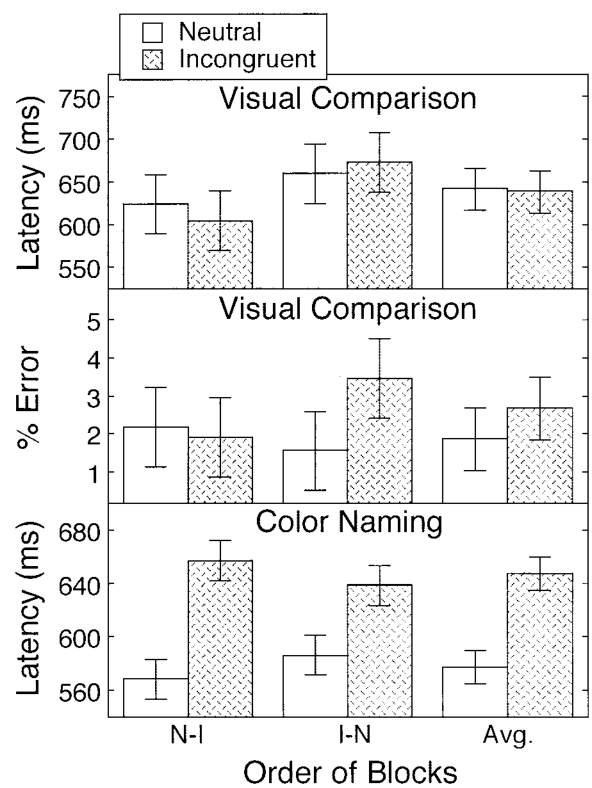

Figure 6. Mean response latency and mean percentage of error on the visual-comparison task and mean response latency on the color-naming task in Experiment 5 as a function of block type and order of block type (neutral block first [N-I], incongruent block first [I-N], and average [Avg.]). Error bars show 95% within-subject confidence intervals and are appropriate for assessing block-type effects.

the color-naming task, so no analysis of color-naming errors is reported.

The mean response latencies and mean percentages of errors on the visual-comparison task are shown in the upper and middle panels of Figure 6, respectively. This figure shows data in the visual-comparison task collapsed across the variable of same versus different character pairs. We averaged across this variable because it had no effect, nor did it interact with block type or block order ($Fs < 1$). Typically, responses to same pairs are faster than responses to different pairs in visual matching tasks, but the size of this effect depends substantially on the extent to which different pairs are discriminable from one another (D. A. Taylor, 1976). In Experiment 5, the eight characters were visually very distinct, and this is probably why there was no advantage for the same condition. An ANOVA of response latencies with block type and block order as the independent variables found no reliable effects, $Fs < 1.4$. The main effect of block type was only 3 ms, with the larger mean in the neutral block rather than the incongruent block, clearly indicating that there was no hint of an interference effect on the visual-comparison task. The power of this experiment to detect an interference effect of approximately the same magnitude as that seen in the word-naming task of Experiment 1 (50 ms) was estimated to be .87. An ANOVA of the error data revealed one significant effect, an interaction between block type and block order, $F(1, 14) = 5.02$, $MSE = 1.86$. This interaction indicates that error rates were higher in the incongruent block when that block came first. Overall, however, there was no main effect of block type, $F(1, 14) = 2.79$, $MSE = 1.86$. The higher error rate in the incongruent block was mainly due to 2 subjects who received that block first and whose error rates were in excess of 7%.[1]

These results suggest that the modulation effect is not due to a general influence of color naming of words on encoding of arbitrary visual forms. Further, the effect does not seem to operate on general decision or response generation mechanisms involved in the binary decision making of the sort required for the visual-comparison task.

Experiment 6

We have demonstrated that there is substantial modulation of word-naming performance consequent to the naming of a word's color. This effect vanishes when a visual-comparison task is substituted for word naming, indicating that modulation is specific to some process that is part of the word-naming task. The possibility that we examined in Experiment 6 is that modulation affects some stage or stages of phonological encoding of an orthographic pattern that is or are necessary for the development of an articulatory code. As indicated above, there is evidence to suggest that the lexical-decision task can be performed without constructing such a code (Hino & Lupker, 2000; Waters & Seidenberg, 1985). Therefore, we used a lexical-decision task in place of the word-naming task. If the phonological coding hypothesis is correct and if the lexical-decision task as conducted here can be completed without such coding, then we would expect little or no modulation of lexical decisions by naming the colors of colored words. Although the failure to find modulation of lexical decisions (in what is clearly a demanding reading task) may seem counterintuitive, we are not saying that this task would not yield switch costs if it were used in standard task-switching paradigms. In these other situations, switch cost typically is based on a comparison between runs of repeated performance of a given task and performance after a task switch. As we have argued above, the modulation effect we have obtained is inherently part of the switch cost if switching occurs between competing tasks applied to bivalent stimuli. However, our paradigm measures the modulation of a task with other sources of switch cost removed because those sources are present in both incongruent and neutral conditions.

Method

Subjects. Eighteen subjects were tested.

Materials. A set of 60 critical words and 60 critical pronounceable nonwords was constructed. These items were all four to six letters in length. The normative frequency of the words ranged from 34 to 787 occurrences per million, with a median of 125. The 60 critical words and 60 nonwords were each arranged as three lists of 20 items for assignment to tasks. One list of each type of item was assigned to serve as letter strings on the lexical-decision task in the neutral block, another set of word and nonword lists was assigned to serve as letter strings on the lexical-decision task in the incongruent block, and the remaining lists were to serve as color stimuli on color-naming trials in the incongruent block. Assignment of the lists of words and nonwords to these three tasks was counterbalanced across subjects. An additional set of 20 words and 20 nonwords was created for use on lexical-decision practice trials, and a set of 30 words and 30 nonwords was constructed for use on task-switching practice trials. The same five colors as in the previous experiments were used for the color-naming task.

Procedure. The procedure was identical to that of Experiment 5, except that the first task on every task-switching trial required subjects to classify a letter string printed in black as a word or a pronounceable nonword. For this lexical-decision task, the stimulus was equally often a word or a nonword. As before, the stimulus presented for the second task was printed in color, and the task was to name that color. In the incongruent block, the stimulus that carried the color was equally often a word or a pronounceable nonword. In the neutral block, the color was always carried by a row of asterisks. Subjects pressed one of two labeled buttons mounted on a response box as rapidly as possible to indicate their decision. The testing session began with 40 practice trials involving just the lexical-decision task. The practice phase was followed by a neutral block and an incongruent block of task-switching trials, with block order counterbalanced across subjects. Each task-switching block began with 20 practice trials followed by 40 critical trials.

Results and Discussion

Response latencies outside the range of 100 ms to 3,000 ms on the color-naming task (0.4%) and response latencies outside the range of 100 ms to 2,000 ms in the lexical-decision task (0.2%) were excluded from the analyses reported here. In addition, 2.1% of color-naming trials were excluded because of inappropriate triggering or failures of the voice-activated relay.

Block order had no effect on color-naming performance, so we present data from that task collapsed across that variable. A Type I error rate of .05 was used in all analyses. Two analyses were of

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[1] To check the possibility that the influence of block type on error reflects a speed–accuracy trade-off that prevented an interference effect from emerging in the latency data, we reanalyzed the data while excluding the 2 subjects whose error rates were over 7% in the incongruent block. With those 2 subjects excluded, there was no sign of an influence of block type on response latency or error rate, $Fs < 1$.

interest. In the first, we compared mean latency of color-naming responses for word and nonword stimuli in the incongruent block. Mean latency was reliably shorter for words (654 ms) than for nonwords (683 ms), $F(1, 17) = 6.86$, $MSE = 1{,}049$. In the second analysis, we compared color naming in the neutral and incongruent blocks, averaging across words and nonwords in the latter case. As in the earlier experiments, latencies were longer in the incongruent block (668 ms vs. 592 ms), $F(1, 17) = 67.29$, $MSE = 781$. Four subjects made 1 error each in the incongruent block, and no errors were made in the neutral block. Because there were so few errors, no statistical analysis of error data was conducted.

The color-naming data, then, produced one new result, namely, that responses were slower to nonword items than to words. This outcome is similar to the small color-naming latency advantage found by Monsell et al. (2001) for high-frequency words over pseudowords. Most of the words used in the present experiment were in the same frequency range as Monsell et al.'s high-frequency words, so our result is consistent with their finding. In addition, however, the pseudowords used by Monsell et al. were matched to the words on a variety of variables, such as length and onset. Our nonwords were not matched to the words. For example, whereas 12 of the critical words shared onsets with one of the five color names used in the experiment, 20 of the nonwords did so. The difference in color-naming latency found here, then, could be due in part to differences between the words and nonwords on some structural characteristic, or it could be due to the context of task switching in which the color-naming task was embedded. Further work is needed to examine these possibilities.

Mean response latencies and the percentage of error for word and nonword targets on the lexical-decision task are shown in Figure 7. Separate analyses were conducted for each type of item, although it is clear from Figure 7 that responses to words were made more quickly and more accurately than were responses to nonwords. We applied an ANOVA to latency data for word targets and found no effect of block type or block order, $F\text{s} < 1$, although the interaction approached significance, $F(1, 16) = 4.28$, $MSE = 1{,}075$. The pattern of means for the interaction indicates that subjects were about 20 ms slower in the second block of trials, regardless of whether that block was the neutral or incongruent block. There clearly was no evidence of an interference effect on lexical-decision trials involving words, as the mean latencies for the neutral and incongruent blocks were nearly identical (622 ms vs. 623 ms).

An ANOVA of the nonword latency data revealed a significant interaction, $F(1, 16) = 4.53$, $MSE = 3{,}168$, with the opposite pattern to that seen with words. Namely, there was a reduction in response latency of about 40 ms on the second block of trials. Neither the block-type nor the block-order main effects were reliable, $F\text{s} < 1$. As with word targets, there was no sign of an effect of block type (776 ms vs. 772 ms for the neutral and incongruent blocks, respectively). The interaction effects seen with word targets and with nonword targets indicate that subjects slowed their responses to words and speeded their responses to nonwords as they moved from the first to the second block of trials, an effect reminiscent of the criterion shift reported for word naming by T. E. Taylor and Lupker (2001). However, this pattern was unaffected by whether asterisks or letter strings carried the color on the color-naming task. Analyses of the percentage of error

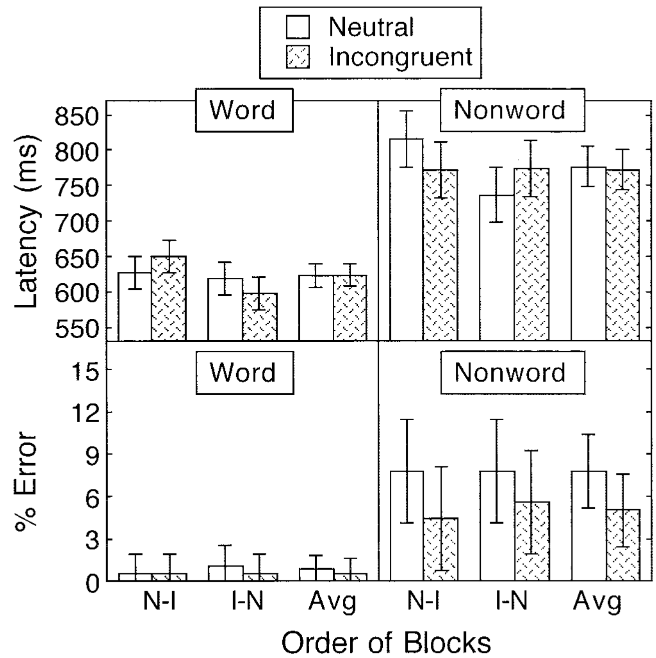

Figure 7. Mean response latency (upper panels) and percentage of error (lower panels) for words and for nonwords on the lexical-decision task in Experiment 6 as a function of block type and order of block type (neutral block first [N-I], incongruent block first [I-N], and average [Avg.]). Error bars show 95% within-subject confidence intervals and are appropriate for assessing block-type effects.

produced no significant effects, $F\text{s} < 1$ for words and $F\text{s} < 2.6$ for nonwords.

The primary result of interest in Experiment 6 was the lack of an influence of block type on lexical-decision responses either for words or for nonwords. When these two item types were combined, there still was no effect of block type, $F < 1$. Because of the relatively greater stability of response latencies to word targets, it was in this condition that Experiment 6 had the greatest power to detect an effect of block type on lexical-decision responses. The estimated power to detect an effect of the magnitude seen in Experiment 1 (50 ms) was .99.

The lack of a modulation effect on lexical decision is consistent with the idea that an aspect of phonological encoding, used in word naming but apparently not in lexical decisions, is at least one of the processes affected by modulation. Although we can tentatively conclude that a locus of modulation is specific to the construction of a phonological code, another possibility exists. In substituting the lexical-decision task and, for that matter, the visual-comparison task of Experiment 5 for the word-naming task, subjects responded by making a binary decision and a manual response instead of a vocal one. If the modulation effect seen in the word-naming experiments is simply attributable to suppression of an overt articulatory response, then no such effect should be seen when a task is used that still requires construction of a phonological code but that no longer demands overt articulation.

Experiment 7

To rule out the possibility that modulation effects emerge as the result of the suppression of an overt articulatory response, we used a word-reading task that does not require subjects to overtly articulate but continues to demand the construction of a phonological code. The task we used was a phoneme-detection task in which subjects were to decide whether a target word contained a specified phoneme. Responses were made manually, as in Experiments 5 and 6, and required a binary decision (i.e., was the phoneme present or absent).

Method

Subjects. Twenty-four subjects were tested.

Materials. A set of 120 critical words, all containing one occurrence of the letter *a*, was constructed. For 60 of these items, the *a* contributed to producing a long *a* sound (/e/) in the normal pronunciation of the word (e.g., *wave*, *drain*, *stay*), whereas for the other 60 words, the *a* participated in producing a different sound (e.g., *share*, *dream*, *cattle*). The critical words ranged from four to six letters in length and from 16 to 808 occurrences per million in frequency, with a median frequency of 97. The 60 critical words of each type were arranged as three lists of 20 items each for assignment to the three different conditions of the experiment: phoneme detection in the neutral block, phoneme detection in the incongruent block, and color naming in the incongruent block. Assignment of lists to conditions was counterbalanced across subjects so that each word was seen exactly once by each subject and each word appeared equally often in each condition. Additional sets of 40 and 60 words, each with half of its words containing the critical /e/ sound, were constructed for use in a phoneme-detection practice phase of the experiment and for practice on task-switching trials, respectively. For the color-naming task, the same colors were used as in the previous experiments.

Procedure. The procedure was identical to that of Experiment 5, except that subjects were instructed to determine whether the designated phoneme /e/ was present in a word instead of being asked to make a lexical decision. /e/ words and non-/e/ words appeared with equal frequency in both phoneme-detection and color-naming tasks. Subjects responded by making manual responses, as in Experiments 5 and 6.

Results and Discussion

Response latencies outside the range of 100 ms to 3,000 ms on the color-naming task (0.3%) and on the phoneme-detection task (0.1%) were excluded from analyses. In the color-naming task, an additional 2.4% of trials were excluded because of inappropriate activation or failures of the voice-activated relay.

Color-naming response latencies were not affected by block order, so the analyses we report here collapsed over that variable. A Type I error rate of .05 was used in all analyses. Color naming in the incongruent block was not reliably different for words containing the /e/ sound and for words not containing that sound (686 ms vs. 696 ms), $F < 1$. However, mean response latency was significantly longer in the incongruent block than in the neutral block (691 ms vs. 592 ms), $F(1, 23) = 110.81$, $MSE = 1{,}058$. Across all subjects, a total of 2 color-naming errors were made in the neutral block and 3 errors were made in the incongruent block, so no statistical analyses of errors were carried out. These results show that, as in the earlier experiments, subjects took substantially longer to name colors when they were embodied in words (or letter strings) than when they were carried by a row of asterisks.

Response latencies on the phoneme-detection task were modulated by block order, so the analyses reported here included that variable. The presence versus absence of the target /e/ sound did not interact with any factors, so we collapsed across that variable in the analyses we report. We simply note that subjects were quicker to respond when the /e/ sound was present in a word than when it was absent (901 ms vs. 1011 ms), $F(1, 22) = 36.98$, $MSE = 7{,}858$. Mean response latencies and the percentage of error for the phoneme-detection task are shown in Figure 8. An ANOVA of the latency data revealed a significant effect of block, $F(1, 22) = 4.92$, $MSE = 3{,}580$, with longer mean latency in the incongruent block than in the neutral block (976 ms vs. 937 ms). This 39-ms effect is of comparable magnitude to that seen in Experiments 1 and 4. Although the effect of block order was not significant, $F < 1$, that variable did interact with block type, $F(1, 22) = 7.88$, $MSE = 3{,}580$.

As can be seen in Figure 8, the interaction arose because the block-type effect was present only among subjects who were given the incongruent block first. This pattern of results reflects a practice effect, whereby subjects responded more quickly on the second block of trials than on the first block of trials in the phoneme-detection task. The lack of practice when the neutral block was presented first obscured the interference effect for that group of subjects, just as it exaggerated the effect for subjects who were presented the incongruent block first. Averaging over these two groups of subjects takes into account the influence of practice and yields a significant main effect of block type, as reported above. Had there been no underlying effect of block type and only an effect of practice, we would have obtained a clear crossover interaction like that seen for lexical decision in Figure 7. The ANOVA applied to the percentage of error data for the phoneme-detection task produced no reliable effects.

The results of Experiment 7 clearly demonstrate that modulation of word processing can be found in a task that requires a binary decision and manual responding instead of a naming response. Moreover, we conducted an additional task-switching experiment, not reported in detail here, that was similar to Experiment 6, except

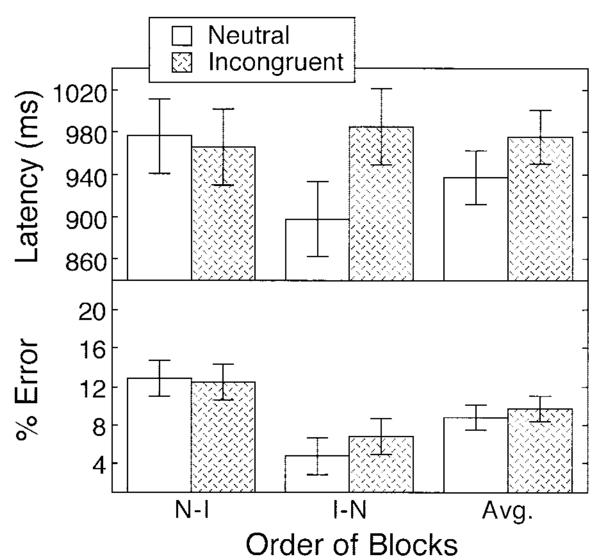

Figure 8. Mean response latency on the phoneme-detection task in Experiment 7 as a function of block type and order of block type (neutral block first [N-I], incongruent block first [I-N], and average [Avg.]). Error bars show 95% within-subject confidence intervals and are appropriate for assessing block-type effects.

that instead of presenting words and nonwords in a lexical-decision task, we presented pseudohomophones (e.g., *brane*, *hoap*) and pronounceable nonwords (e.g., *naft*, *perd*). Subjects classified items using manual responses according to whether the items would sound like real words if pronounced aloud (a phonological lexical-decision task). As in the phoneme-detection task of Experiment 7, subjects showed a significant interference effect of 41 ms on this phonological lexical-decision task such that longer decision times were observed in the incongruent block (where the color in the color-naming task was carried by a pseudohomophone or a nonword) than in the neutral block (where the color was carried by asterisks). Furthermore, we also conducted a replication of Experiment 7 and obtained a significant 63-ms interference effect on the phoneme-detection task. Thus, when the task that precedes color naming requires phonological processing, response latency is reliably modulated by the nature of the stimulus presented in the color-naming task. We found no modulation in a visual-comparison task that did not require word reading, nor did we find modulation in a lexical-decision task. It remains to be seen whether modulation can be found in other tasks, especially reading tasks, that do not rely as heavily on phonological processes as do word naming or phonological decisions.

General Discussion

The literature on the cost of switching between tasks includes accounts based on endogenous shifting of task set (e.g., Baddeley et al., 2001) and exogenous cuing of task set (e.g., Rogers & Monsell, 1995). An additional claim holds that shifting from a bivalent stimulus incurs a persistent cost associated with resolving the competition involved in making a nondominant response to one dimension of the stimulus and avoiding a dominant response to the other dimension (Allport et al., 1994; Allport & Wylie, 2000). In typical task-switching paradigms that use bivalent stimuli, there is the possibility that the persistent cost of competition resolution is a substantial component of the observed task-switch cost. It should be possible to observe the cost of this competition resolution on subsequent performance of the dominant task even when it is applied to a univalent stimulus. The present experiments were designed to investigate this persistent cost, separate from the influences of endogenous and exogenous control of task set. Both the neutral trials and the incongruent trials used in our experiments involved a switch between word naming and color naming; therefore, both involved a switch cost of some form. The crucial difference between these two trial types was that in the incongruent trials, color naming was performed on a bivalent stimulus (a colored word), whereas in the neutral trials, color naming was applied to a univalent stimulus (a colored string of asterisks). Thus, competition resolution would arise only in the incongruent trials. The persistent cost of this resolution was revealed by comparing word-naming performance (in a task where the words were always presented in black) in incongruent and neutral trials.

Our experiments indicate that word naming incurs a large cost due to interference generated from naming the color in which a previous word was presented. Strikingly, this effect was no greater for a small set of words presented repeatedly, even in the color-naming task, than for a much larger set of words, each of which was presented only once. Second, we showed that modulation of word naming accrues over time, requiring between 2 and 10 consecutive incongruent trials to reach asymptotic levels. It is not clear in exactly which run of the 10 trials modulation was learned, but this question was not of great concern here. Instead, it is important to note that virtually no modulation was obtained when single incongruent and neutral trials were alternated, and only a small amount of modulation was found when runs of 2 consecutive trials of a particular type were presented. However, runs of 10 trials yielded a full modulation effect. Moreover, once modulation was learned, it dissipated rapidly over the course of a few trials when subjects shifted to a run of neutral trials. When subjects encountered a new run of incongruent trials, the modulation effect was reinstantiated after only one trial. Also, this reinstatement of modulation coincided with a reduction in the latency to name the color of words. No such change in color naming was observed in the neutral condition (where color was carried by a row of asterisks). Thus, there is good evidence that modulation of word reading mitigates the competition experienced during the naming of a color carried by a word.

Finally, we provided preliminary evidence that modulation of word-identification processes was specific to tasks involving the construction of a phonological code from a visually presented word. In particular, although word naming and phoneme detection showed reliable modulation, two tasks that presumably did not require phonological encoding, visual comparison and lexical decision, did not. Our tentative conclusion, then, is that resolving competition during the naming of word color affects processes specific to the construction of phonological codes. Moreover, the results of Experiment 1 imply that this influence is not confined to the particular word that carries the named color but generalizes across a large set of words.

Although we have shown that the modulation effect on word naming generalizes beyond the specific words encountered in the color-naming task, a question for future research concerns the particular conditions of conflict resolution that lead to modulation. In our experiments, conflict consistently involved competition between the habitual naming response to a word and the less practiced task of color naming. It remains to be seen whether modulation also can be observed when neither member of a conflicting task pair is habitual and conflict arises only because of task-set activation. If there is nothing special about conflict based on task dominance (i.e., one of two task sets is habitual), then we would expect modulation to occur in any situation in which competition occurs between two active task sets. A further question concerns the generalizability of our account to tasks other than word reading. For example, would modulation be observed in other naming tasks, such as picture naming or digit naming, or in tasks not requiring responses based on the pronunciation of words? Assuming that modulation does extend to a wider variety of task combinations, it becomes an important and general component of task-switch costs, as we discuss below.

Implications for Accounts of Task Switching

Many experiments on task switching indicate that costs persist even when subjects have ample time to prepare for an upcoming task switch (e.g., Allport & Wylie, 2000; Meiran, 1996; Rogers & Monsell, 1995). One explanation for this residual switch cost is that subjects cannot fully configure a task set until it is exogenously cued by a specific stimulus (Rogers & Monsell, 1995). Our experiments used intervals of approximately 1 s to 3 s between response to the color stimulus and the onset of the word stimulus on the next trial. Given previously reported results, intervals of this length should have provided ample time for subjects to prepare for execution of our word-identification tasks (word naming in Experiments 1–4, lexical decision in Experiment 6, and phoneme detection in Experiment 7), and therefore any cost of switching from color naming to word identification can reasonably be considered residual in nature.

This observation raises the possibility that performance on our word-identification tasks could have been determined in part by a failure to adequately configure the task set until the occurrence of a stimulus that acts as the exogenous cue. If we further assume that the influence of exogenous cuing is stronger when switching from a task involving a bivalent stimulus (naming the color of a word in our case) than when switching from a task involving a univalent stimulus (naming the color of a row of asterisks), then one might argue that our modulation effect is, in fact, another instance of residual switch cost driven by exogenous cuing. Indeed, the pattern of switch costs seen in Experiment 2 (see Figure 3), in which we used a procedure similar to that used by Rogers and Monsell (1995), is consistent with this assumption. In that experiment, switch cost, defined by Rogers and Monsell as the difference in response latency between the first and second items presented for word naming, was larger in the incongruent condition (involving a switch from a bivalent stimulus) than in the neutral condition (involving a switch from a univalent stimulus). Conceivably, the cost of switching from naming the color of a bivalent stimulus to naming a univalent word reflects the inability to fully configure the word-naming task set until the occurrence of the target word. In the case of switching from a univalent stimulus in the color-naming task, we might conjecture that there is less dependence on exogenous cuing.

However, our experiments provide strong evidence against this proposition. First, the need for exogenous cuing to fully establish a task set should affect performance regardless of the particular task to which one is switching. But we have shown that the modulation that underlies our results—namely, the effect of bivalent color naming on a subsequent task—depends crucially on the nature of that task. In particular, we found no evidence of modulation of either lexical-decision or visual-comparison tasks. For both of these tasks, as with the word-naming and phoneme-detection tasks, exogenous cuing ought to be necessary for task-set configuration after the execution of bivalent color naming.

Second, the modulation effect accrues over time. It is much greater when subjects carry out at least 10 consecutive incongruent trials (each trial consisting of the naming of a univalent word stimulus followed by the naming of the color of a bivalent item) than when only 1 or 2 such trials are presented consecutively. This observation, coupled with the task specificity discussed above, implies that subjects are learning to modulate specific aspects of their word-reading behavior. There is nothing in the Rogers and Monsell (1995) account of exogenous cuing to imply that reliance on such cuing to configure task sets is a learned skill.

Third, and most important, we have good evidence that modulation of word naming benefits performance in the color-naming task, but only if color is carried by a word. This outcome indicates that modulating a component process of word naming has adaptive significance in a situation where word naming interferes with the competing task of color naming. The theoretical construct of exogenous cuing may apply to word naming in our paradigm, but it surely has no explanatory force in regard to the link between slowed word naming and the subsequent naming of a color carried by a word. Modulation of word naming, once learned, results in an immediate benefit to color naming after the first trial of a block of incongruent trials and persists over the subsequent trials of that block (see Figure 5). This pattern is consistent with the claim that slowed word naming involves suppression of a component process of reading and leads to reduced interference when naming the color of a bivalent stimulus. There is nothing in the exogenous cuing account that would explain why a slower word-naming response is associated with a faster color-naming response.

We have argued that the concept of exogenous cuing cannot provide an adequate account of the modulation effect that we have obtained. In addition, we can consider whether some of the residual switch cost reported by Rogers and Monsell (1995) and ascribed by them to exogenous cuing might receive an alternative interpretation based on the modulation of component processes. The general paradigm used by Rogers and Monsell involves presenting two consecutive trials of the same task followed by another two trials of another task, with both tasks involving bivalent stimuli. Their definition of a switch cost is the difference between performance on the first trial of each task and the subsequent trial. Performance is much slower on the first trial because, in their account, configuration of task set is incomplete until the occurrence of a relevant stimulus but is fully established by the time the next stimulus is presented. Alternatively, the observed difference between the first and second trial performances is fully compatible with the idea that performance of the first trial is slow because modulation of a component process of the relevant task has occurred as a result of interference generated during the immediately preceding task. The modulation rapidly dissipates after a single trial, just as it did in our Experiment 4 (see Figure 5). Thus, the difference between two consecutive trials of the same task can be attributed to the dissipation of modulation rather than to the exogenous cuing of a task set (for a similar idea, see Allport et al., 1994; Meiran, 1996; Meiran et al., 2000). We note that switch costs found by Rogers and Monsell were generally much larger than the modulation effects on word naming that we report. In most of their experiments, however, both tasks involved bivalent stimuli, whereas our word-naming task always involved a univalent stimulus. In cases in which Rogers and Monsell's subjects switched to a task involving a univalent stimulus (their no-crosstalk condition), switch costs were of a magnitude similar to ours.

Another interpretation of residual switch costs is based on transfer or priming effects from a previously executed task that interfere with attempts to execute a currently designated task (Allport et al., 1994; Allport & Wylie, 2000). These influences can be of two types. First, there is persisting activation of the previous but now conflicting response to an attribute of a particular stimulus (e.g., having earlier named the color red carried by a word, one must now name a word printed in red). Second, this persisting activation could, in principle, also maintain a task set that conflicts with performance after a task switch (e.g., having earlier performed a color-naming task in which color was carried by a word, one must now name a word). Both of these forms of activation have some plausibility if the word-naming task involves presenting a word printed in color.

The question is whether these ideas are plausible when applied to our procedure. The stimulus-specific version of persisting activation could not operate during our experiments because the word-naming task was always to name a word printed in black, and black never appeared as a color in the color-naming task. It seems unlikely that there is a tendency on the part of the subject to name the color (black) of the printed word in the word-naming task when no such response ("black") was ever required in the color-naming task. Moreover, words that appeared in the word-naming task never were color names, so there is no reason to expect the word-naming stimulus to evoke competing color-naming responses. Activation as the persistence of a more general color-naming procedure would have to have the following characteristics, given our results: (a) It would have to persist even though the word-naming stimulus is univalent, (b) it would have to be specific to tasks that appear to depend on phonological processes, and (c) it would not be an automatic consequence of executing a single color-naming response to a bivalent stimulus but would require multiple trials to develop. In addition, such activation would have to survive despite the possible effects of backward inhibition that would mitigate against persistence of the abandoned task set of color naming (Mayr & Keele, 2000).

Allport and colleagues (e.g., Allport & Wylie, 2000) also suggested that residual switch cost can be generated by the persistent suppression of a response or process that competes with the execution of a task (e.g., suppression of word naming when naming the color of a printed word). This cost may then be observed when the subject switches to a task that requires the suppressed response or process. A substantial contribution to switch cost of the sort seen by Allport and colleagues is attributable to response conflict associated with specific items. For example, naming the color of a particular color word leads to difficulty in naming that word on a subsequent trial because the act of reading the word has been suppressed during the generation of the earlier color-naming response (Allport & Wylie, 2000, Experiment 3). In addition to their work on stimulus-specific suppression, Allport and Wylie obtained some evidence that suppression affects a general word-naming process by using color words never seen in their Stroop color-naming task (although those corresponding colors had been presented). They found that both these words and color words that had been presented in the Stroop color-naming task showed the same degree of slowing when presented subsequently in black for word naming. This effect was larger than the 50-ms effect we obtained. It is possible, then, that part of word-naming suppression is specific to the particular semantic category, in this case colors, that constituted the conflicting response dimension. The remaining component appears to be quite general, extending equally to noncolor words seen either repeatedly or only once in the course of an experimental session. Our results indicate that suppression of word naming is even more general than suggested by Allport and colleagues' results, not restricted either to color words or to a small set of noncolor words repeatedly presented in the context of color naming and word naming.

The account of task modulation that we have developed bears some resemblance to the concept of backward inhibition, in which a just-executed task set is inhibited to prevent it from intruding during execution of a subsequent task (Mayr & Keele, 2000). Both our account and the backward inhibition account assume a form of suppression that generalizes across items. Backward inhibition is assumed to occur unconditionally as a result of task disengagement (Mayr & Keele, 2000, p. 23). Presumably such inhibition would occur even when the disengaged task applies to a univalent stimulus, provided there is a possibility of upcoming competition involving a bivalent stimulus in which the disengaged task must be avoided (Mayr, 2001). The incongruent trials of our paradigm are an instance of exactly this situation (naming a univalent stimulus, then naming the color of a bivalent stimulus). However, the modulation effect that we observed was not found under all circumstances and, in particular, did not occur when incongruent and neutral trials were presented in alternating runs (our Experiment 3). If backward inhibition were responsible for the modulation of word reading, disengagement of word reading on an incongruent trial should have led to slower word reading on neutral trials. Modulation occurred only when runs of at least two consecutive incongruent trials alternated with runs of at least two neutral trials. Therefore, there is reason to argue that backward inhibition is not the mechanism responsible for the modulation of word reading we have shown.

Learned Modulation of Component Processes

In our account, the basis for modulation of word naming is the competition occurring during performance of the color-naming task in the incongruent condition. Competition between task sets in the Stroop paradigm has been modeled by Cohen, Dunbar, and McClelland (1990), who used the concept of task nodes to represent the demands of word reading and color naming. To carry out color naming, subjects must suppress or gate the word-reading task node to prevent competition with the color-naming response. This gating is only partially successful because of the highly overlearned nature of the word-reading response, yielding the interference seen when color naming occurs in the presence of a word. What aspect of a Stroop stimulus activates the word-reading task node? Monsell et al. (2001) suggested that it is the properties of the letter string's orthography, including pronounceability detected by rapid activation of orthographic-to-phonological connections. According to Monsell et al., gating occurs at an early stage of processing, reducing the competition between the word-reading and color-naming task sets and, in most circumstances, preventing the development of response competition.

There are a number of reasons to argue that this gating account of the mechanism of competition resolution in the Stroop paradigm is incomplete. First, contrary to the assumption made by Monsell et al. (2001) that suppression of the word-reading task set prevents lexical access, there is evidence that words carrying colors in a color-naming task show priming on a subsequent lexical-decision task equivalent to that shown by words that are read during a study phase (Szymanski & MacLeod, 1996). However, it may be the case that gating of early stages of reading merely slows lexical access instead of preventing it completely, and this form of slowing is sufficient to overcome competition from the word during color naming. But even if gating occurs at an early stage, there is clearly a second kind of suppression that can operate in the Stroop paradigm. We have shown that a few seconds after a color-naming response to a colored word, no slowing of a lexical-decision task occurred. Thus, there appears to be no residual cost of competition during color naming on the general task of word reading despite the fact that substantial costs are found when word-naming responses are measured. Gating at an early stage of word reading, if it has occurred during the color-naming task, is therefore unlikely to exert a persistent influence on a subsequent word-reading task.

The kind of suppression that we suggest is measured in our experiments deals with later stages of processing, where phonological codes are constructed (see Burt, 2002, for a similar proposal regarding the modulation of phonological processes in the color Stroop task). Thus, tasks such as word naming and phoneme detection but not necessarily lexical decision are affected. The nature of the conditions that lead to modulation of earlier stages of processing remains an open question. For example, presenting words for reading in color instead of in black might invoke a form of interference during word reading that would lead to the gating of perceptual inputs that could have consequences on subsequent color-naming and/or word-reading trials. For an explicit distinction between control mechanisms differentially affecting stimulus and response representations, see Meiran (2000).

It is interesting to consider the possible neural correlates of the form of modulation that we have demonstrated. We know that selective attention to particular visual dimensions such as color or motion demonstrates enhancement of activity in domain-specific cortical regions (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990). The enhancement of activation in cortical regions associated with particular types of knowledge can be observed even when selective attention is applied to a bivalent Stroop-like stimulus in which one dimension dominates another. Banich et al. (2001) showed increased activation in a number of cortical regions relevant to word processing by comparing brain activity during color naming when color was carried by an incongruent color word versus when color was carried by a neutral word. This increase in activation was attributed to priming of the pathway between words and color concepts as a by-product of the task demands of selectively attending to the color dimension. However, the subtraction for regions of activation in the incongruent versus neutral conditions of the Banich et al. study is not very likely to identify the neural mechanism that permits selective responding to a color rather than a word when presented with a Stroop stimulus. Because the subtraction was between two conditions in which color was carried by a word, the resulting differences were unable to reveal a suppression mechanism that we assume is common to both types of words.

Our paradigm is a viable candidate for investigating the neural mechanisms that support selective responding to a bivalent stimulus even when the word does not refer to a color. We have demonstrated that (a) suppression applies to all words, not just those that have appeared on color-naming trials; (b) the amount of suppression is substantial in relation to the relatively fast and overlearned activity of naming a word; (c) suppression may be selective to processes specific to phonological encoding; and (d) suppression is relatively long-lasting in that it can be detected even after a delay of about 3 s after a color-naming response. These characteristics invite further examination of whether it can be shown that the activity of specific cortical regions is altered during modulation of word naming.

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Received June 25, 2002
Revision received April 15, 2003
Accepted April 15, 2003 ■