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EXAMINING THE TIME COURSE OF PRIME EFFECTS ON STROOP PROCESSING[1]

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Summary.—This study was conducted to assess the effect of priming on the Stroop task over time. Color-congruent, color-incongruent, and neutral stimuli were randomly presented. Five prime conditions were also used. The prime conditions included valid color, invalid color, valid word, and invalid word primes and no prime. Primes were presented to 8 subjects at varying stimulus onset asynchronies ranging from −200 msec., i.e., 200 msec. before the color-word stimulus, to 200 msec., i.e., 200 msec. after the color-word stimulus. Analysis suggested the facilitory or inhibitory effects of semantic information on the Stroop task are reduced when the prime follows the color-word stimulus by 200 msec. This implies 200 msec. are needed to make the proper color response. A model is proposed to account for the findings. Methodological considerations for studies using priming and the Stroop task are also discussed.

Stroop (1935) presented subjects with a matrix of color-words printed in different colors. He also presented subjects with a similarly constructed matrix of blocks using the same colors. Stroop found that it took subjects longer to name the color print when the word matrix was used compared to the matrix of blocks. This increase in response time for color naming has been called Stroop interference. Researchers have typically explained Stroop interference in terms of relative speed of processing (Morton & Chambers, 1973; Posner & Snyder, 1975) or automaticity (LaBerge & Samuels, 1974; Shiffrin & Schneider, 1977). Both of these explanations assume that words are processed faster than colors which allows the word information to "beat" the color information to the response bottleneck and produce interference. This assumption implies that by presenting the slower color information sufficiently before the word information, Stroop interference could be eliminated or reversed. One way to test this hypothesis is to prime the color information before the color-word stimulus is presented.

Warren (1972) presented prime lists from semantic categories before a color-irrelevant test stimulus. For example, DOG, CAT, HORSE were presented before the word DOG appeared in blue print. In this case it took longer to say "blue" than if no prime list was presented. Similar effects were found if the test word was a category label such as ANIMALS, suggesting that the activation of the categorical information pertaining to a particular word is sufficient to produce interference. Other studies have similarly shown that context can influence Stroop interference (Conrad, 1974; Merrill, Sperber, & McCauley, 1981; Dosher & Corbett, 1982; Whitney, 1986).

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McClain (1983) varied the relatedness of a prime to the color-word stimulus. Primes either implicitly or explicitly primed color and provided either primary or secondary word activation (see Table 1). For example, "red" served as an explicit color-secondary word-activation prime to the color-word "blood." There were also implicit color primes, e.g., "apple" as the prime and "fire" as the color-word, primary word-activation primes, e.g., "nail" as the prime and "nail" as the color-word, implicit color-primary word-activation primes, e.g., "apple" as the prime and "apple" as the color-word, and explicit color-primary word-activation primes, e.g., "red" as the prime and "red" as the color-word. The prime was presented for 500 msec. followed by a dark exposure field for 200 msec. The color-word stimulus was then presented until a voice key was activated when the subject named the color aloud. All color-word stimuli were presented in incongruent print so the word "blood" appeared in yellow, green, or blue but never in red. After the response to the color was made there was a 600-msec. interval during which the color-word was still visible. Subjects had to recall the prime at the end of this interval. McClain found that implicitly priming the color increased interference. Primes that provided activation of a primary word also increased interference. The amount of interference was increased when both the color and word dimensions were primed. Thus, implicit activation of the color-primary word and explicit color-secondary word-activation primes produced more interference than implicit color and primary word-activation primes alone. She also found that explicit color-primary word-activation primes produced facilitation.

While these studies suggest that a color-irrelevant word can produce interference with color naming if its meaning is primed before the test trial,

TABLE 1
EXAMPLES OF PRIMES AND COLOR-WORDS USED BY MCCLAIN (1983)

Prime Condition	Stimulus	
	Prime	Color-word
Explicit color and	red	blood
Secondary word activation	blue	sky
	green	grass
Implicit color activation	apple	fire
	water	berry
Implicit color and	apple	apple
Primary word activation	water	water
	lettuce	lettuce
Primary word activation	nail	nail
	drink	drink
Explicit color and	red	red
Primary word activation	blue	blue
	green	green

they were not specifically designed to address the time course of priming effects. Therefore, the time at which a color prime can eliminate or reverse Stroop interference on a subsequent color-word stimulus has not been determined.

Researchers who have examined the temporal processing of the Stroop effect have typically done so by separating the two dimensions of the color-word stimulus and presenting both dimensions at varying stimulus onset asynchronies (Dyer, 1971, 1974; Dyer & Severance, 1973; Thomas, 1977; Glaser & Glaser, 1982). For example, Dyer (1971) tested the hypothesis that short stimulus onset asynchronies increase interference and long stimulus onset asynchronies decrease interference. He presented the word information first and color second separated by stimulus onset asynchronies ranging from 0 to 500 msec. On any given trial, a word appeared in black, a time interval elapsed, and then the same word appeared in a color. Dyer found that longer stimulus onset asynchronies decreased interference for color naming and that interference was greatest at shorter stimulus onset asynchronies (e.g., 40 and 60 msec.). In general, this research suggests that the word information must precede or follow the color information by less than 100 msec. for maximum interference to occur (cf. MacLeod, 1991). However, these studies did not include primes.

This study examined the time course of priming effects on Stroop interference and facilitation by combining these two areas of research. Both word and color primes were presented while varying the stimulus onset asynchrony between the prime and the color-word stimulus. Consistent with previous research, it was anticipated that primes would produce the most interference and facilitation when presented within 100 msec. of the color-word stimulus.

METHOD

Subjects

Ten undergraduate students from the University of Georgia participated in the experiment for class credit. Visual acuity was tested using a Landolt C with a gap subtending .3° of visual angle at 103 cm viewing distance. Color vision was examined using the Color Vision Screening Inventory (Coren & Hakstian, 1987). All subjects had normal or corrected-to-normal visual acuity and normal color vision. Two of these subjects, however, were eliminated from the study for inadequate performance on the word-naming task used to assess the perceptibility of the stimuli, so eight subjects participated in the experimental trials.

Apparatus

Stimuli were presented on a CRT monitor using the Graves and Bradley (1988) timing and screen control routines for QuickBASIC. Response times were measured from stimulus offset to key press. Four keys corresponding to the four colors (red, green, yellow, and blue) were used. Red and green were coded using the middle and index fingers of the left hand and the "z" and "x" keys, respectively. Similarly, yellow and blue were coded using the right hand and the "." and "/" keys.

The monitor was placed at the fixed viewing distance of 103 cm so that the longest word, YELLOW (.5 cm high × 1.8 cm wide), subtended no more than 1° of visual angle. Stimuli were randomly presented .17° above or below fixation to eliminate strategy effects. Color values were measured photometrically at .1 footlamberts for each color.

Design

Three stimulus conditions were used. Color-congruent stimuli were color-words displayed in the corresponding color print, e.g., the word RED in red print. Color-incongruent stimuli were color-words presented in a different color print (e.g., the word RED in green print). Finally, neutral stimuli, words having no inherent color meaning (TOP, CHAIR, LADDER, and BOOK), were presented in each of the four colors. There were also five prime conditions (Table 2). Valid color primes correctly primed the color of the printed item to be named. Invalid color primes primed a color other than the color to be named. Similarly, valid word primes correctly primed the semantic information to be ignored while invalid word primes primed a word other than that presented in the color-word stimulus. Finally, there was also a no-prime condition. The stimulus and prime conditions were randomly presented. Color primes were presented as blocks equal in size to the color-word stimulus. Stimulus onset asynchronies between the prime and color-word stimulus varied from −200 msec. to 200 msec. (−200, −100, −80, −60, −40, 0, 40, 60, 80, 100, 200). Negative stimulus onset asynchronies indicate that the prime was presented before the color-word stimulus and

TABLE 2
EXAMPLES OF FIVE PRIME CONDITIONS

Stimulus		Prime
Word	Color	
GREEN	green	Valid Word = GREEN
		Invalid Word = BLUE
		Valid Color = block of green
		Invalid Color = block of red
		No Prime = blank screen
CHAIR	red	Valid Word = CHAIR
		Invalid Word = BOOK
		Valid Color = block of red
		Invalid Color = block of blue
		No Prime = blank screen

Note.—This list is not inclusive of all stimulus and prime combinations.

positive stimulus onset asynchronies indicate that the prime was presented after the color-word stimulus. There were 825 practice trials (3 word types × 5 prime conditions × 11 stimulus onset asynchronies × 5 trials) and 1650 experimental trials (3 × 5 × 11 × 10 trials).

Procedure

Blocks of color were presented in the center of the screen for 100 msec. Subjects were instructed to press the key corresponding to the color block as quickly and as accurately as possible. Accuracy feedback was given every ten trials. There were 48 such trials, and an accuracy rate of 90% was needed to continue.

To assess whether subjects could see the color or word presented at brief durations, two sets of test trials were administered. First, each of the eight words was presented in white print at fixation for varying durations (20, 40, 60, 80 msec.) followed by a mask. Subjects read the words aloud as they appeared on the screen while the experimenter recorded errors. In the second set of test trials, blocks of colors were similarly presented except the responses were recorded on the computer. All subjects included in the study maintained 100% accuracy rates for both word naming and color naming when the words and colors were presented for 80 msec.

Subjects were then instructed that the words were going to appear in one of the four colors and that they needed to respond to the color of the print. They were also informed that a prime would appear on some trials and that the prime would either be a word or a color block. Subjects received the practice trials followed by the experimental trials. During the priming trials, a fixation point appeared at the center of the screen for 750 msec. A prime appeared at fixation followed by the color-word stimulus which was presented either .17° above or below fixation. For example, one trial might consist of a yellow prime followed by the word BLUE. Subjects pressed the key that corresponded to the color of the print. Primes appeared for 80 msec. and the color-word stimuli appeared for 100 msec. Prime condition, stimulus condition, and stimulus onset asynchrony were randomly presented. Rest opportunities were provided every 100 trials to minimize fatigue effects and were terminated by the subject with a key press.

RESULTS

A 3 × 5 × 11 repeated-measures analysis of variance of response times was conducted. Analysis yielded a significant main effect of word type, prime condition, and stimulus onset asynchrony. The two-way interaction of prime condition and stimulus onset asynchrony and the three-way interaction of word type × prime condition × stimulus onset asynchrony were also significant (see Table 3). However, the adjusted F statistic using both the Greenhouse-Geisser technique and Box's epsilon was not significant (Box, 1954;

Geisser & Greenhouse, 1958; Huynh & Feldt, 1970), so it cannot be safely concluded that these interactions reflect the variables manipulated (cf. Hays, 1988). Only the three main effects of word type, prime condition, and stimulus onset asynchrony were significant.

TABLE 3
RESULTS OF THE 3 × 5 × 11 REPEATED-MEASURES ANALYSIS OF VARIANCE

Analysis	F	p
Response Time Analysis		
Main Effect of Word Type	6.88	.05
Main Effect of Prime Condition	12.53	.0001
Main Effect of Stimulus Onset Asynchrony	3.51	.001
Error Rate Analysis		
Main Effect of Word Type	7.77	.05
Main Effect of Prime Condition	40.58	.0001
Main Effect of Stimulus Onset Asynchrony	4.46	.0001

The mean response times were 538.39 msec. for color-congruent words, 584.63 msec. for color-incongruent words, and 555.91 msec. for neutral words. The 46.24 msec. difference between color-congruent words was responded to significantly faster than that between color-incongruent words ($F_{1,7} = 9.58$, $p < .02$). However, there was no statistically significant difference between color-congruent and neutral words and color-incongruent and neutral words.

Differences between the mean response times for the five prime conditions are summarized in Table 4. Valid color primes produced faster response times than no prime, a valid word prime, an invalid color prime, and an invalid word prime. Surprisingly, no prime produced slower response times than all other prime conditions.

TABLE 4
MEAN DIFFERENCES AMONG RTS FOR EACH PRIME CONDITION COMPARED TO VALID COLOR-PRIME CONDITION, F RATIOS, AND SIGNIFICANCE LEVELS BY COMPARISON

Condition	Difference Between Mean RTs	F	p
Valid Word	34.45	7.45	.03
No Prime	88.58	50.89	.0002
Invalid Word	30.57	22.75	.002
Valid Color	55.30	17.79	.004

Table 5 shows differences between the mean response times for each stimulus onset asynchrony. Response times were fastest when the prime came 200 msec. after the color-word stimulus. Primes presented 100 and 60 msec. before the color-word stimulus produced faster response times ($F_{1,7} = 6.62$, $p < .04$ and $F_{1,7} = 10.98$, $p < .02$, respectively) than the simultaneous presentation of the prime and stimulus (i.e., 0 msec.).

TABLE 5
DIFFERENCES IN RT (MSEC.) AMONG STIMULUS ONSET ASYNCHRONY CONDITIONS COMPARED TO THE 200-MSEC. CONDITION

Condition (msec.)	Differences Between RTs (in msec.)
−200	70.96
−100	48.43
− 80	56.31
− 60	46.72
− 40	68.81
0	92.02
40	62.13
60	61.76
80	59.66
100	95.91

A similar analysis was conducted for error rate data. There was a significant main effect of word type, prime condition, and stimulus onset asynchrony. All three two-way interactions and the three-way interaction were significant. However, Greenhouse-Geisser and Box's epsilon showed that the interaction between word type and prime condition and the three-way interaction may not be due to experimental manipulations. Therefore, only the interactions between word type × stimulus onset asynchrony ($F_{20,140} = 1.99$, $p < .01$) and prime condition × stimulus onset asynchrony ($F_{40,280} = 3.92$, $p < .0001$) were statistically significant.

Fewer errors were associated with color-congruent words ($F_{1,7} = 9.09$, $p < .02$) and neutral words ($F_{1,7} = 16.14$, $p < .005$) compared to color-incongruent words. There was no statistical difference between color-congruent and neutral words. Valid color primes produced fewer errors than an invalid color prime ($F_{1,7} = 51.63$, $p < .0002$) and an invalid word prime ($F_{1,7} = 74.53$, $p < .0001$). Error rate remained above 12% when the prime appeared before the color-word stimulus. Error rate dropped below 10% when the prime and stimulus appeared at the same time and when the prime followed the stimulus by 40 or 200 msec. Error rates were at least 12% when the prime followed the stimulus by 60, 80, and 100 msec.

The word type × stimulus onset asynchrony interaction is shown in Fig. 1. There was relatively no difference among word types when the prime preceded the color-word. However, when the prime followed the color-word stimulus more errors were made to the color-incongruent words. There was no difference among prime conditions across stimulus onset asynchrony except for the invalid color-prime condition (Fig. 2). When the invalid color prime preceded the color-word stimulus, error rates were relatively high but decreased as stimulus onset asynchrony approached zero. Error rates then steadily increased from 40- to 60-msec. stimulus onset asynchrony to signifi-

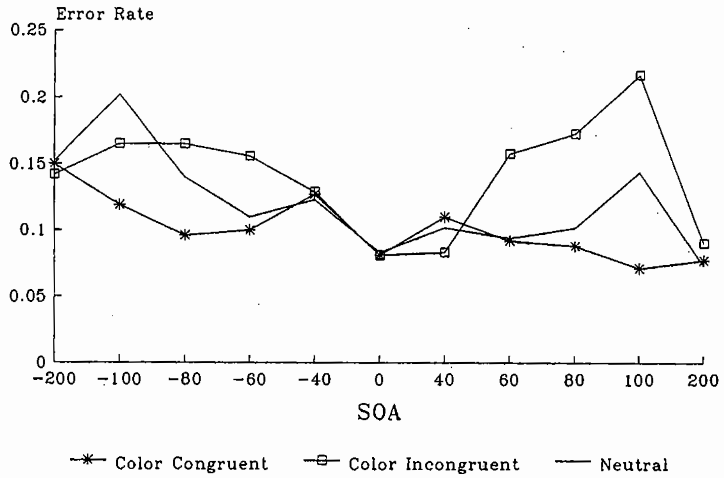

FIG. 1. Error rates for the stimulus condition × stimulus onset asynchrony interaction

cantly higher levels at 80 and 100 msec. before declining once again at 200-msec. stimulus onset asynchrony.

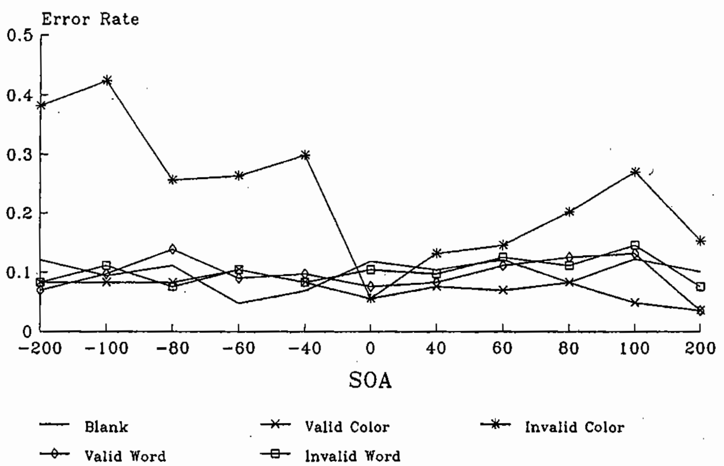

FIG. 2. Error rates for the interaction of prime condition × stimulus onset asynchrony

DISCUSSION

The purpose of this experiment was to provide converging results on the time course of the Stroop effect using integrated stimuli. Koch and Brown

(Koch, 1993; Koch & Brown, submitted) have found that the greatest reduction in response time occurs after an integrated color-word stimulus has been presented for 200 msec. Similarly, primes presented 200 msec. after the color-word stimuli produced the shortest and most accurate responses, i.e., least interference. This suggests that the processing of an integrated Stroop stimulus may not be influenced by additional information for at least 200 msec. A further implication is that 200 msec. of processing an integrated Stroop stimulus is needed before the effects of the word on color naming can be reduced.

Word primes, whether valid or invalid, had little effect on processing the color-word stimulus. This finding is inconsistent with previous research on priming. For example, McClain (1983) found that color-associated word primes produced Stroop interference. However, in the present experiment, when the word prime was the same as the color-congruent word there was no significant decrease in response time. There was also no significant increase in response time when the word prime was the same as the color-incongruent word. Methodological differences between these studies may account for this discrepancy. Although McClain (1983) intermixed word types and prime conditions as in the present study, she did not use color primes. Other research using primes or pretrial cues suggests that the cues can be used to develop processing strategies that improve performance (Logan & Zbrodoff, 1979; Cheesman & Merikle, 1984). Once again, these studies used words as cues, not color. The fact that cues can affect processing and that little information is available to assess the effects of color cues or primes on developing a strategy suggests that the findings of the present experiment may be qualitatively different from results obtained in previous research. For instance, it is feasible to assume that subjects only used information from color primes. If so, this would account for the increase in response time and error rate for invalid color primes compared to valid color primes and for the relative absence of facilitation and interference caused by valid word and invalid word primes.

There were also differences in prime and stimulus duration between the present study and that conducted by McClain (1983). McClain presented the prime for 500 msec. compared with 80 msec. in the present experiment. In addition, McClain presented the color-word stimulus until subjects made a verbal response. Stimuli were presented for only 100 msec. in the present study. Finally, stimulus onset asynchrony was not manipulated by McClain. Primes were always presented 200 msec. before the color-word stimulus. These differences and the results of the present experiment warrant additional research using the priming task to explore the attentional processing of color-word Stroop stimuli and the time course of priming in the Stroop task. For example, research varying the duration of the prime needs to be conducted to judge whether allowing additional processing time for the prime information increases the amount of facilitation and interference obtained. Systematic investigation of stimulus onset asynchrony is also necessary.

In light of these methodological considerations, the present findings can be explained by the following model (see Fig. 3) which is composed of two control loops (Carver & Scheier, 1981). The first loop is associated with the decision-making process and the second loop is associated with making the response. Initially the color-word is processed as a whole, i.e., the color is part of the word and not processed as a separate dimension. The color-word information is compared to the task demands (a) which require that a response to the color be made. The response is initially generated based on the word information (b) only since the word label is available before the color label and the word satisfies the task demand of a color response. Once a response is decided upon, the appropriate response must be made. Therefore, the response information enters the response process loop. The first step in the response process is to identify the appropriate key press (d). This response is then verified (e) before the trial is terminated by the actual key press (g). Response information is used as feedback in the motor response to guarantee that the appropriate key is pressed (e to c) and as feedback in the decision-processing loop to guarantee that the correct response was selected (e to b). Previous research has shown a reduction in response time for color-word stimuli presented for 200 msec. or more (Koch, 1993; Koch &

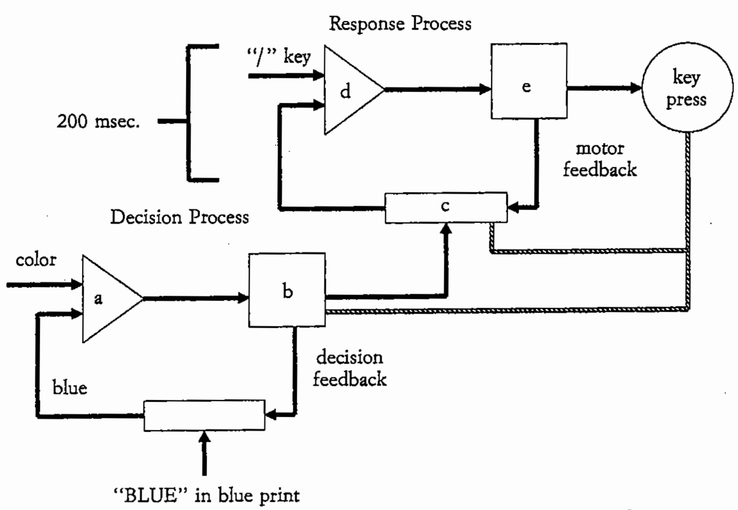

FIG. 3. Proposed decision and response feedback loops used in processing integrated Stroop stimuli

Brown, submitted) and the present study shows a reduction in response time and errors when the prime occurs 200 msec. after the color-word stimulus. These findings appear to provide evidence that it takes the response-processing loop 200 msec. before verification begins and feedback is available.

This model allows for both the reduction of response times when integrated stimuli were presented for more than 200 msec. (Koch, 1993; Koch & Brown, submitted) and the decrease in response time and error rate found in the present study when the prime was presented 200 msec. after the color-word stimulus. For example, a color-congruent stimulus is presented (BLUE). The color-word information enters the decision-processing loop and the response "blue" is selected. "Blue" then enters the response-processing loop which selects the appropriate key press for "blue," i.e., "/." Before the key press is made the response is verified. Therefore, response information is used as feedback to the decision loop and the response-processing loop. If the color-word stimulus is presented for more than 200 msec. or the color information is primed at this time, the color information is readily available in the decision-processing loop. The response "blue" is then compared to the color blue. Since the response and the color match, the decision process is finished. When the response and color match, the speed of decision processing is enhanced. The "/" key is then verified as the correct response for a blue stimulus and the key is pressed. Neutral words, however, are unrelated to the task demands which call for the naming of a color. Therefore, a response based on the word does not constitute a valid response and the word is ignored, allowing a response to be generated based on the color of the stimulus.

Color-incongruent words are processed in the same way as color-congruent words until the response is verified. When the response-feedback information enters the decision-processing loop the response and color are found to be incongruous. Decision processing is reactivated to identify the color of the color-word stimulus. The result of this processing then enters the response-processing loop to identify the appropriate key press. This additional processing results in longer response times and increases the probability of processing error.

In summary, determining the time course of priming on the Stroop task has received little attention (MacLeod, 1991) and involves a number of methodological considerations which need to be addressed. The present study suggests that it takes approximately 200 msec. to determine the color response to an integrated color-word stimulus. Additional research is required to address the time course of priming on the Stroop task and to help clarify effects found due to methodological differences between priming studies. The model presented to account for the present findings may serve as a guide for research regarding the effects of priming in the Stroop task when integrated color-word stimuli are used.

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