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Response set modulates stroop interference

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RESPONSE SET MODULATES STROOP INTERFERENCE

A Thesis

Presented to

The Faculty of the Department of Psychology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

by

Tao-Chung Wang

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ABSTRACT

RESPONSE SET MODULATES STROOP INTERFERENCE

by Tao-Chung Wang

Dissociation of the word and color aspects of Stroop stimuli can reduce “word-based” semantic conflict on incongruent trials and thus reduce Stroop interference. Two experiments involving 81 participants each manipulated response characteristics rather than stimulus characteristics. In each, the participants indicated the physical color of the stimulus via a verbal response. Experiment 1 used a two-color Stroop task (red, green); Experiment 2 replicated Experiment 1 with the exception that the responses were to be “red” or “not red” rather than “red” or “green.” This response set manipulation reduced Stroop interference. In all cases, the Stroop task was the second of two tasks in a Psychological Refractory Period (PRP) design. The PRP manipulation has been shown to be sensitive to limitations on cognitive functioning that are not apparent under single-task conditions.

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Introduction

Human beings usually operate under conditions of some uncertainty in an environment full of competing stimulus inputs. To cope with this environment, humans must be able to focus attention and process goal-relevant information efficiently, while filtering out goal-irrelevant information. The Stroop effect is a paradigmatic laboratory example of a condition requiring the efficient handling of conflicting information.

The Stroop effect is a robust phenomenon with a long history of study in cognitive psychology. It is the classic example of the human failure to attend selectively: the meaning of the color words impairs naming the print color. Similarly, although reading the word is “favored,” color word naming is also slightly hindered by an incongruent print color.

The Stroop effect has accrued theoretical interest because the effect is produced by pitting the automatic process of word reading against the less automatic process of color naming. Because reading is more automatic and speedy than naming, the latter suffers intrusions from involuntary word reading, but reading is much less hampered by conflicting print color. There is an asymmetry in the observed interference between color-word reading and color naming of Stroop stimuli. When reading the names of colors, the background color of the word is relatively easy to ignore. However, in color naming, the meaning of the word tends to influence how quickly the participant responds with the correct color. For example, identifying a background color, such as red, is quicker when the word is RED than when the word is GREEN. In the latter case, the word GREEN interferes with the process of identifying the red ink.

Overall, when considered in isolation, word reading is quicker than color naming. The relative speed-of-processing account of the Stroop effect begins with the fact that words are read faster than colors are named (Fraisse, 1969). This speed difference is particularly critical when two potential responses (e.g., one from a word and one from an ink color) compete to be the response that will be executed. The general interpretation of this phenomenon is referred to as response competition: the two codes are seen as racing to control the final output, and the time cost of this competition is *interference*. Response competition can be modeled as resulting from a “horse race” type process (speed-of-processing) or from a strength-of-association process. Stroop (1935) posits the latter view: the associations between the word stimuli and the reading response are stronger than between the color stimuli and the naming response.

Posner and Snyder (1975) elaborated on the idea of relative speed-of-processing by indicating that the Stroop effect arises because of response competition between vocal responses to the printed word and the ink color. The amount of interference depends upon the time involved. Since words are read faster than colors can be named, a color naming response receives stronger interference from the word than the reverse. Posner and Snyder hypothesized that color naming and reading are processed in parallel and without interference until response output.

An integrative review of the Stroop effect by MacLeod (1991) suggested that the relative speed-of-processing hypothesis requires three assumptions. First, there must exist parallel processing of the two dimensions of the stimulus at differential speeds. Second, there must contain a limited-capacity response channel into which only one of

the two potential responses can be accepted at a time. Third, the potential response must receive input from several different sources, including preceding trials and other response-set elements.

In the past, the existence of Stroop interference has been argued to clearly illustrate the differences between controlled and automatic processes (Schneider & Shiffrin, 1977). Controlled processes are assumed to be voluntary, to require attention, and to be relatively slow, whereas automatic processes are assumed to be involuntary, to not require attention, and to be relatively fast.

Why is naming the color of a word so difficult? There are several factors that seem to be involved. The most important notion is that reading is automatic and cannot be avoided when the participant is looking at a word. As a result of the automaticity of reading, there is a semantic activation of the material that is presented (Monahan, 2001). Because the response a participant must make in the Stroop task is triggered by a semantic decision, the automatic activation of an alternative response to the one the participant is supposed to make (presuming that the word and color are incongruent) can produce response competition with the desired response. Interestingly, if the word is presented in advance (in black), prior to the color change then it will produce little interference with naming the physical color that the text changes to. It is as if the reading response has already been cleared through the system (Besner & Stolz, 1999) or that the word / color connection within the stimulus has been decoupled.

The prevalent explanation that accounts for automaticity is that processing one dimension requires much more attention than does processing of the other dimension

(Cattell, 1886). Thus, naming the ink color draws more heavily on attentional resources than does reading the irrelevant word. Moreover, reading the word is seen as obligatory, whereas naming the ink color is not. Presumably, this imbalance derives from a life history of reading words as opposed to naming ink colors. Under this theory, the asymmetry that is the fundamental characteristic of the Stroop task can be accounted for. Words are read automatically; colors require considerably more attention to be named (LaBerge & Samuels, 1974; Posner & Snyder, 1975; Schneider & Shiffrin, 1977; Logan, 1978; Hunt & Lansman, 1986). Based on this theory, level of automaticity is seen as a gradient that develops with learning. Thus, word reading is very automatic, and color naming is much less automatic. More automatic processes could then interfere with less automatic processes, but less so the other way around. Based on this, Cohen, Dunbar, and McClelland (1990) proposed an alternative explanation of the Stroop effect, which does not distinguish between automatic and controlled processing. Instead, they proposed that automaticity is a continuum, and that Stroop interference depends on the relative degree of learning of the respective tasks, not on processing speed per se. According to this view, asymmetries in performance such as those observed in the Stroop task can be accounted for by relative differences in experience with processing the stimulus dimensions.

According to Posner and Snyder (1975), the real strength of automaticity theories lies in their ability to capture priming situations. Priming occurs through the automatic activation, the same mechanism that is used to explain Stroop interference. If the irrelevant words are color related, they automatically activate their “alternative” color

response, resulting in interference (Logan, 1980; Clark, 1996). More recent Stroop research indicates that Stroop interference is not as unavoidable as strong automaticity theories would suggest. Stroop Interference is demonstrably malleable through manipulating context (e.g., Sabri, Melara, & Algom, 2001). In a particularly strong example of this malleability, Besner, Stolz, and Boutilier (1997) challenge the idea that reading Stroop letter strings is completely automatic. They found that when all but one of the letters of a color name was printed in a neutral color and the participant was instructed to name the ink color of the single colored letter, Stroop interference was reduced or even eliminated.

The explanation proffered by Besner and Stolz (1999) builds on the idea of *mental set* as a powerful determinant of performance. Different stimulus contexts may induce different mental sets and thus change the default processing of the stimulus. Besner et al.'s findings are at odds with the widely accepted assumption that Stroop word reading is automatic. In a replication of Besner et al.'s study, Catena, Fuentes, and Tudela (2002) computed priming effects in addition to the standard Stroop interference. Their interference results replicated those of Besner et al.'s, thus providing strong support for the role of mental set as a determinant of performance. It seems that coloring only a single item in the stimulus word causes the observer to perform letter-based search on the color words and thus are less likely to "automatically" read the stimulus word. The single-letter Stroop task may provide a situation in which the participant can use low-level perceptual mechanisms to engage an early selection process to avoid the other "stimulus irrelevant" lexical aspects of the target. If these letters are individually

selected early in processing, then the automatic mechanisms of whole-word reading may not be engaged. The implication that automaticity could be lessened by the stimulus context set suggests strong limits on what might otherwise be considered an “automatic” process.

This thesis further investigates the role of mental set vis-à-vis Stroop interference using a manipulation of response set rather than of the stimulus set. Experiment 1 used a two-color variant of the standard Stroop task. The word RED or GREEN presented completely in the color red or green was used instead of the word RED, GREEN, BLUE, or YELLOW completely in the color red, green, blue, or yellow. The response set was changed from “red” or “green” in Experiment 1 to “red” or “not red” in Experiment 2. Experiment 1 thus provides a baseline against which to determine if the influence of word reading on Stroop color naming was impacted by the manipulation of the response set in Experiment 2. A comparison of the results of Experiments 1 and 2 will determine if a response-set manipulation could produce the same magnitude of reduction in Stroop interference as observed by Besner et al. (1997).

The rationale was that Stroop interference is affected by highly practiced mental skills that become rapid and automatic once acquired. The skilled readers process strings of letters up to the level of word names and meaning even when there is no intent to read the word; the reading process cannot be suppressed. Thus, participants are unintentionally reading and, thus, being confused by letter strings, which are irrelevant to the task and that they have been instructed to ignore, when they are trying to name incongruent ink colors. According to Besner et al.’s explanation, even

unintentional reading of letter strings is at least as fast, if not faster, than naming ink colors, and participants can more easily suppress the unintentional tendency to name words: if those words are unrelated to the responses that they wish to make such as naming the ink colors. On this account, coloring only a single letter in a word at fixation, or naming the print color of a color word determined by its alternative word, induces a set that promotes processing that either is simply nonlinguistic, or does not engage the lexical / semantic level. In both cases, the Stroop effect can be dramatically reduced. By changing the response set from “red” and “green” to “red” and “not-red,” a comparable shift in default processing to that obtained with the stimulus set manipulation may be obtained.

The Use of the PRP Paradigm.

Previous studies using the PRP Paradigm have shed light on the type of interference that occurs when two simple tasks are done concurrently (e.g., Hick, 1948; Welford, 1959; Pashler & Johnston, 1989). Response time (RT) to the second stimulus is often delayed by several hundred milliseconds. Logically speaking, when responding appropriately to a stimulus, participants must somehow transform the perceptual information about the stimulus into knowledge of which response to make and activation of an action plan to execute the appropriate response (Fagot & Pashler, 1992). This processing can be broken into at least three stages: a perceptual processing stage, a response selection stage, and a response execution stage (Sternberg, 1969). According to Welford (1980), response selection commonly constitutes a bottleneck – a stage of processing shared by both tasks that only one of the tasks can be engaged in at

any time. It is widely held that the most commonly observed interference in the PRP paradigm, occurs predominantly at response selection. In other words, the PRP effect is generally caused by an inability to perform the central operations required for Task 2 (e.g., response selection) at the same time as the central operations required for Task 1 (Luck, 1998; Pashler & Johnston, 1989). Although there is some debate about the specific interpretation of PRP interference and the special circumstances required to bypass what can be considered a central processing bottleneck, the basic empirical finding of changes or no changes in the magnitude of the observed Stroop interference across stimulus onset asynchrony (SOA) is sufficient for the interpretation of the current experiments. An expansion of the fairly traditional “bottleneck” view of the logic of the PRP paradigm is presented by Van Selst, Ruthruff, and Johnston (1999); with alternate treatments presented by Meyer and Kieras (1997), and a more recent clarification of constraints presented by Hazeltine, Ruthruff, and Remington (2006).

Regardless of the particular theoretical cast one interprets PRP effects within, prior use of the Stroop task in PRP paradigms has shown that the magnitude of Stroop interference is not affected by the time between the onset of the stimulus for Task 1 and the onset of the stimulus for Task 2 (Fagot & Pashler, 1992). In technical terms, Stroop interference is additive with SOA. An additional bonus of using the PRP paradigm is that investigating the stability of this additivity with SOA across the response manipulations proposed for this set of experiments should allow insight into whether or not “typical” Stroop type processing is occurring despite the manipulation of the response set.

In all cases, in the current experiments, the Stroop task is the second of two tasks within a PRP design. The PRP paradigm was selected since it has been shown to be sensitive to limitations on cognitive functioning that are not apparent under single-task conditions. As an example of such use, Fillmore and Van Selst (2002) found that alcohol did not significantly impair either of two “simple” cognitive tasks, but were able to demonstrate reliable dose – and SOA – dependent dual-task cognitive impairments when the two tasks were paired within a PRP design, providing an important constraint on models of human cognitive architecture.

EXPERIMENT 1

Experiment 1 provided a baseline against which to compare the results of Experiment 2. The difference between the experiments was that the response set for Experiment 1 was “red”/ “green,” and the response set for Experiment 2 was “red”/ “not-red.” Using more participants than usual for comparable PRP experiments ($N = 77$ valid participants in Experiment 1; $N = 71$ in Experiment 2 as compared to $N = 20$ from Fillmore & Van Selst, 2002; $N = 20$ -32 from McCann, Remington, & Van Selst, 2000; and $N = 20$ -40 from Van Selst & Jolicoeur, 1994) ensured that the current experiment had adequate statistical power (Moyer, Finney, & Swearingen, 2002).

Method

Participants.

Eighty-one San Jose State University undergraduates ranging in age from 18 to 29 ages (34 men) participated in partial fulfillment of a course requirement. All participants reported normal or corrected-to-normal vision, no color vision deficits, nor any difficulty discriminating the tones. Of these participants, 77 were retained for analysis. The remainder had error rates in excess of 20% on one or both tasks (two participants excluded) or unusually slow response times on either Task 1 (>1000 ms, one additional participant) or Task 2 (>1000 ms, one additional participant) and thus were eliminated from the study.

Stimuli.

Task 1. The Task 1 stimulus consisted of either a pure tone (1,000 Hz) or a short burst of white noise generated by the computer. The tones were presented for 100 ms.

Task 2. The Task 2 stimulus was one of eight stimuli. These stimuli were the two possible color words (RED, GREEN) presented in one of two colors (red, green) at either upright or rotated 180 degrees in the picture-plane. The print color words were presented in 24 point Times Roman font. The RED was presented using rgb values of 255,0, on the IBM 0-255 intensity scale; the GREEN was presented using rgb values of 0,255,0. Each print color word fit within a rectangular area of 1.41 x 0.94 degree of visual angle against a black background at a viewing distance of 70 cm. The stimuli were always presented at the center of the screen.

Apparatus.

The experiment was developed using the E-prime experiment generation program from Psychology Software Tools Inc. An IBM 500 MHz microcomputer equipped with a Pentium II processor driving a Voodoo 3dfx graphics card, a unidirectional desktop microphone, and a 19" Viewsonic Color monitor (display area = 37 cm x 28 cm) controlled stimulus presentation and timing. A standard computer keyboard was used to collect responses to the tone discrimination task. An E-prime response box was used to collect voice onset latencies for the Stroop task.

The participants were tested individually in a darkened room, accompanied throughout by the experimenter who provided the voice recognition information via a response box containing three response buttons ("red," "green," or spoiled).

Procedure.

The participant was to perform two tasks on each trial. The first task was a tone judgment. The second task was a Stroop task. The first task had the participant

indicate, via key-press (“k” or “m”), whether the tone that was presented was a high tone or a low tone. The second task had the participant identify the physical color of the visual stimulus by saying the color aloud into a microphone. The instructions to the participants were to perform both tasks as quickly and as accurately as possible.

Each trial began with the presentation of a white fixation cross at the center of the screen for 800 milliseconds (ms). Immediately after the fixation cross disappeared, the tone was presented. The Stroop stimulus followed the tone after a stimulus onset asynchrony (SOA) of 50, 150, 300, or 800 ms. The Stroop stimulus was response-terminated or timed-out after 5000 ms. After the Stroop stimulus disappeared, the computer waited for the experimenter to indicate which verbal response had been made and then presented response feedback for each of Task 1 and Task 2. The fixation cross for the next trial appeared after an inter-trial interval of 1500 ms. The experimental session consisted of one block of 50 practice trials followed by four blocks of 64 experimental trials each, and the whole session required approximately 30 minutes.

Design.

The experiment used a 2 x 2 x 2 x 4 x 2 within-subject factorial design. The factors were tone (high, low), color (red, green), congruency (congruent, incongruent), stimulus onset asynchrony (50, 150, 300, 800), and stimulus orientation (upright, upside-down). The design was replicated once per block. The order of trials was random.

Results

Separate three-way within-subjects analyses of variance (ANOVAs) were conducted for response times and error rates on the individual cell means from each of Task 1 and

Task 2. The factors were Congruency, Stimulus Onset Asynchrony, and Stimulus Orientation. The response time analyses were performed on mean response times of those trials within each cell that were responded to in more than 100 ms, less than 4500 ms, and in which both Task 1 and Task 2 were responded to correctly.

Task 1 Analyses.

RT1. Task 1 response times showed a slight tendency for inter-task dependence, increasing 39 ms as SOA increased, $F(3, 228) = 15.08$, $MSe = 12554.37$, $p < .001$. There was neither a main effect of Congruency, $F < 1$, nor Rotation, $F(1, 76) = 1.29$, $MSe = 7724.26$, $p = .26$. A nonlinear 2-9 ms variation in the congruency effect across SOA produced a marginal interaction between SOA and Congruency, $F(3, 228) = 2.40$, $MSe = 3812.40$, $p = .068$. No other interactions were significant, ($Fs < 1.61$, $ps > .18$).

An additional analysis, including tone as a factor, was also performed. Additional findings were that High tone responses (pressing 'k') were 29 ms slower than low tone responses (pressing 'm'), $F(1, 76) = 29.92$, $MSe = 10964.36$, $p < .001$. The effect of SOA was modulated by Tone, $F(3, 228) = 3.15$, $MSe = 4287.97$, $p = .026$: the SOA effect on high tone response times was 45 ms; the SOA effect on low tone response times was 31 ms. There was a marginal interaction between Tone and Rotation, with an orientation effect for high tones (9 ms) but not for low tones (1 ms), $F(1, 76) = 3.38$, $MSe = 4438.15$, $p = .07$.

Accuracy on Task 1. The mean overall accuracy on Task 1 was 94.8%. Accuracy decreased monotonically with decreasing SOA (97.4% at the 800 ms SOA to 91.8% at the 50 ms SOA), yielding a significant main effect of SOA, $F(3, 228) = 44.28$, $MSe =$

.008, $p < .001$. The only other significant finding came with the inclusion of Tone as a factor. The SOA effect was more pronounced for low tones (97.7% to 90.6%) than for high tones (97.1% to 93.0%), $F(3, 228) = 44.28$, $MSe = .027$, $p < .001$. None of the other effects were significant (all $Fs < 2.37$, all $ps > .128$).

Task 2 Analyses.

RT2. The most salient result was the main effect of SOA, $F(3, 228) = 762.82$, $MSe = 8023.55$, $p < .001$. Short SOA trials were responded to 326 ms slower than Long SOA trials ($M = 892$ ms at the 50 ms SOA, 566 ms at the 800 ms SOA). There were also main effects of Congruency, $F(1, 76) = 347.06$, $MSe = 4924.69$, $p < .001$ and Rotation, $F(1, 76) = 27.21$, $MSe = 3970.81$, $p < .001$. Congruent trials ($M = 703$ ms) were responded to 74 ms faster than incongruent trials ($M = 777$ ms). Rotated trials (731 ms) were responded to 19 ms faster than upright trials ($M = 750$ ms). The Congruency by Rotation interaction, [$F(1, 76) = 40.32$, $MSe = 3380.22$, $p < .001$], was produced by the 39 ms difference across Rotation in the incongruent condition, producing a much larger congruency effect for upright trials ($M = 96$ ms) than for rotated trials ($M = 54$ ms).

The significant two-way interaction between Rotation and SOA, [$F(3, 228) = 2.78$, $MSe = 2080.42$, $p = .042$], can best be understood in the context of the three-way interaction between Congruency, SOA, and Rotation, $F(3, 228) = 3.38$, $MSe = 2527.52$, $p = .019$. Rotated items were responded to faster than upright items across SOA for the Incongruent trials (differences of 38, 42, 46, and 32 ms with decreasing SOA) but reversed for the Congruent trials (differences of 24, -10, -15, and -9 ms with decreasing SOA). The interaction between Congruency and SOA was not significant ($F < 1$). The

additivity of congruency across SOA remained stable even when restricting the RT2 analysis to upright trial data only, $F(3, 228) = 1.41$, $MSe = 4244.24$, $p = .24$. The analysis of Task 2 response times is illustrated in Figure 1.

Accuracy on Task 2. The analysis of Task 2 accuracy is illustrated in Figure 2. The mean overall accuracy on Task 2 was 93.4%. Congruent items ($M = 98.5\%$) were responded to more accurately than Incongruent items ($M = 88.3\%$), $F(1, 76) = 149.39$, $MSe = .021$, $p < .001$. This congruency effect was more pronounced for upright items (14.3% difference) than for rotated items (5.0% difference). This pattern yielded a two-way interaction between Congruency and Rotation, [$F(1, 76) = 106.37$, $MSe = .007$, $p < .001$], as well as a main effect of Rotation on Task 2, [$F(1, 76) = 101.75$, $MSe = .008$, $p < .001$).

Accuracy remained high across SOA for the congruent trials (greater than 98% correct in the upright items). For the upright items, the incongruent accuracy decreased from 86.5% at the 800 ms SOA to 79.1% at the 50 ms SOA. For the rotated items, incongruent accuracy decreased from 95.0% at the 800 ms SOA to 92.1% at the 50 ms SOA. This pattern of data yielded a main effect of SOA, $F(3, 228) = 7.72$, $MSe = .004$, $p < .001$, and interactions between Congruency and SOA, $F(3, 228) = 13.98$, $MSe = .003$, $p < .001$, Rotation and SOA, $F(3, 228) = 3.15$, $MSe = .01$, $p = .026$, and a marginal three-way interaction between Congruency, Rotation, and SOA, $F(3, 228) = 2.53$, $MSe = .003$, $p = .058$. These results suggest that Stroop interference might actually be increasing with decreasing SOA, although minor Task 1 variations in response time and accuracy may be responsible for at least some of this effect.

Experiment 1. Response Times

Figure 1. Response times for Task 1 (thin lines, smaller markers) and Task 2 (thick lines, larger markers) from Experiment 1 across SOA (50, 150, 300, 800 ms). Mean response times are for congruent (darker lines, lighter markers) and incongruent trials (lighter lines, darker markers), across upright (circles) and rotated (squares) trials.

Experiment 1. Accuracy

Figure 2. Accuracy data for Task 2 (thick lines, larger markers) from Experiment 1 across SOA (50, 150, 300, 800 ms). Mean response times are for congruent (darker lines, lighter markers) and incongruent trials (lighter lines, darker markers), across upright (circles) and rotated (squares) trials.

Discussion

The most important finding in Experiment 1 was the statistical additivity of the effect of Congruency across SOA in the response time analysis for Task 2. Even when restricting the RT2 analysis to upright trial data, the congruency effect remained statistically additive across SOA. This is consistent with prior literature (e.g., Fagot & Pashler, 1992). It is clear that the amount of observed Stroop interference does not decrease during the “Task 2 cognitive slack time” during which Task 2 processing is held back until after Task 1 processing clears the bottleneck (Pashler & Johnston, 1989). The only evidence of additional Task 2 information processing during the period of cognitive slack induced by Task 1 occupying the dual-task bottleneck processing stage is the increased Stroop effect evident in the Task 2 accuracy data with decreasing SOA. A speed-accuracy trade-off would suggest that, if anything, Stroop interference is over-additive with SOA. This is an unusual finding that does not replicate reports from previous work. The author of the current study addresses the possibility again after examining the results from Experiment 2.

A second important finding from Experiment 1 is that rotated items produced less Stroop interference than upright items. This phenomenon presumably indicates that rotated items have a weaker S-R relationship than upright items or that the additional difficulty in reading the items impairs the semantic access that would normally produce high levels of Stroop interference.

The clear finding is that the processes leading to Stroop interference are not attenuated during the period of slack time in Task 2 processing while waiting for Task 1

to clear the dual-task bottleneck stage. The working assumption adopted herein is that reading appears to be involuntary (since it produces consequences that are contrary to the task demands) and that, on the incongruent trials, the reading of the word activates the alternate response and thus produces dual-task interference.

EXPERIMENT 2

Experiment 1 was designed to establish the baseline Stroop interference obtained using the particular parameters we selected. The purpose of Experiment 2 was to investigate the consequences of changing the response alternatives to see if the change in response set would produce the same type of reduction in Stroop interference as Besner et al. (1997) observed from changing the stimulus characteristics.

Method

Experiment 2 is a replication of Experiment 1 except that the response set for the Stroop task in Experiment 1 (“red” versus “green”) was replaced by a new response set (“red” versus “not-red”) designed to produce less response conflict with the semantic content of the words. In all other respects the experiment is identical. This experiment used 81 San Jose State University undergraduates ranging in age from 18 to 47 ages (18 men). Of the participants, 71 were retained for analysis. The remainder failed to complete the experiment (one participant), had error rates in excess of 20% on one or both tasks (one additional participant excluded), or had unusually slow response times on either Task 1 (>1000 ms, two participants) or Task 2 (>1000 ms, six additional participants).

Results

Experiment 2 were analyzed in the same manner as for Experiment 1.

Task 1 Analyses.

RT1. Task 1 response times showed a slight tendency for inter-task dependence, showing a 28 ms monotonic increase as SOA increased, $F(3, 210) = 9.29$, $MSe =$

5060.39, $p < .001$. None of the interactions were significant (all F s < 1.38 , all p s $> .17$ except for the two-way interaction between Congruency and Rotation, which was marginal at $F(1, 70) = 2.87$, $MSe = 2001.76$, $p = .095$).

When adding in Tone as a factor, there was a significant main effect of Tone, $F(1, 70) = 7.07$, $MSe = 1917.91$, $p = .01$. High tones were responded to 12 ms faster than Low tones. Outside of the main effect of SOA, there were no main effects or interactions that approached significance. The analyses of Task 1 and Task 2 response time and accuracy are illustrated in Figure 3 and Figure 4.

Accuracy on Task 1. The mean overall accuracy on Task 1 was 95.4%. Accuracy decreased monotonically with decreasing SOA (97.4% at the 800 ms SOA to 92.7% at the 50 ms SOA), yielding a significant main effect of SOA, $F(3, 210) = 36.85$, $MSe = .003$, $p < .001$. Incongruent trials showed more of a decline with SOA than Congruent trials (97.1% to 92.2% vs. 97.2% to 93.3%), producing a significant interaction between Congruency and SOA, $F(3, 210) = 4.26$, $MSe = .002$, $p = .006$, and a significant main effect of Congruency, $F(1, 70) = 12.63$, $MSe = .002$, $p = .001$.

When including Tone as a factor, all of the preceding findings remained stable. There was a three-way interaction between Tone, SOA, and Congruency, $F(3, 210) = 3.40$, $MSe = .005$, $p = .019$. High tone accuracy declined with SOA for congruent trials (2.7%) to a lesser extent than low tone congruent trials (4.7%), high tone incongruent trials (7.1%), or low tone incongruent trials (4.0%). This pattern of data also produced a Tone by Congruency interaction, $F(1, 70) = 7.42$, $MSe = .006$, $p = .008$, and a marginal modulation of the effect of SOA by Tone, $F(3, 228) = 2.39$, $MSe = .005$, $p =$

Experiment 2. Response Times

Figure 3. Response times for Task 1 (thin lines, smaller markers) and Task 2 (thick lines, larger markers) from Experiment 2 across SOA (50, 150, 300, 800 ms). Mean response times are for congruent (darker lines, lighter markers) and incongruent trials (lighter lines, darker markers), across upright (circles) and rotated (squares) trials.

Experiment 2. Accuracy

Figure 4. Accuracy data for Task 1 (thin lines, smaller markers) and Task 2 (thick lines, larger markers) from Experiment 2 across SOA (50, 150, 300, 800 ms). Mean response times are for congruent (darker lines, lighter markers) and incongruent trials (lighter lines, darker markers), across upright (circles) and rotated (squares) trials.

.07. There was also an interaction between Tone and Rotation, with a 0.4% drop from upright to rotated for high tones a 1.0% increase for low tones, $F(1, 70) = 8.26$, $MSe = .003$, $p = .005$.

Task 2 Analyses.

RT2. There was a 365 ms PRP effect, $F(3, 210) = 1024.77$, $MSe = 6824.91$, $p < .001$, and congruent trials ($M = 756.4$ ms) were responded to 17.5 ms faster than incongruent trials ($M = 773.9$ ms), $F(1, 70) = 26.18$, $MSe = 3315.90$, $p < .001$. A significant Rotation by SOA interaction was produced by rotated trials being responded to faster than upright trials at the 800 ms SOA but not at the shorter SOAs, $F(3, 210) = 5.14$, $MSe = 3205.70$, $p = .002$. The main effect of Rotation was not significant, $F(1, 70) = 1.56$, $MSe = 3945.56$, $p = .216$, nor were the other interactions (Congruency by SOA, $F(3, 210) = 1.90$, $MSe = 2366.48$, $p = .13$; $F < 1$ for the others).

Accuracy on Task 2. The mean overall accuracy on Task 2 was 94.0%. Accuracy decreased with decreasing SOA from 95.1% at the 800 ms SOA to 92.0% at the 50 ms SOA. This pattern of data yielded a main effect of SOA, $F(3, 210) = 16.35$, $MSe = .003$, $p < .001$. Congruent items ($M = 95.0\%$) were responded to more accurately than Incongruent items ($M = 93.0\%$), $F(1, 70) = 25.09$, $MSe = .004$, $p < .001$. This congruency effect was more pronounced for upright items (3.7%) than rotated items (0.3%). This pattern yielded a two-way interaction between Congruency and Rotation, $F(1, 70) = 23.71$, $MSe = .003$, $p < .001$, as well as a main effect of Rotation, $F(1, 70) = 16.32$, $MSe = .003$, $p < .001$. No other interactions were significant, all F s < 1 .

Additional Analyses.

Further consideration leads to the additional hypothesis that “red” trials should produce more Stroop interference than “green” trials. The logic of the claim is that the amount of Stroop interference between the “congruent” green trials (GREEN in green producing the response “not”) and “incongruent” green trials (GREEN in red, producing the response “not”) ought to be less pronounced than the more natural “red”/ “green” response pairings. To evaluate this possibility, an additional analysis compared the “red” patterns of Stroop interference separately for “red” and “green” in Experiment 1 against and “not red” in Experiments 2.

For the response time data for Experiment 2, a $4 \times 2 \times 2 \times 2$ within-subjects ANOVA was performed. The factors were: SOA (50, 150, 300, 800 ms), Congruency (congruent vs. incongruent), Rotation (upright vs. rotated), and Correct Response (“red” vs. “not”). The cell means of only 71 of the 72 participants were analyzed since one participant produced no valid response times in one of their cells. Congruent trials ($M = 756$ ms) were responded to faster than incongruent trials ($M = 773$ ms), $F(1, 70) = 27.29$, $MSe = 172540.3$, $p < .001$. This 17 ms congruency effect consisted of a 6.5 ms reversal for the “not” responses (change = -6.5 ms) and a 41 ms effect for “red” responses. In a cross-experiment comparison, this reversal and reduction in the amount of Stroop interference relative to the comparable cells in Experiment 1 (70 ms congruency effect for green, 79 ms congruency effect for red), produced a significant Congruency by Correct Response (red vs. green / not) interaction, $F(1, 145) = 19.2$, $MSe = 109149.6$, $p < .001$. This pattern of results is illustrated in Figure 5.

Figure 5. Response Times for Task 2 from Experiment 1 (circles) and Experiment 2 (squares) across SOA (50, 150, 300, 800 ms). Mean response times are for congruent (solid lines) and incongruent trials (dashed lines), across response type. “Red” is indicated by darker lines and “green” (Experiment 1) or “not red” (Experiment 2) is indicated by lighter lines.

Discussion

The results are clear. The RED / NOT RED Task (Experiment 2) produced less Stroop interference than the RED / GREEN Task (Experiment 1). This result extends Besner et al.'s (1997) argument that changing the stimulus characteristics can modulate Stroop interference. It is now clearly demonstrated that response characteristics also modulate (and can eliminate) Stroop interference. The additional analyses examining the size of the Stroop effect across correct response ("red" in red vs. green, "green" in red vs. green, "red" in red vs. not, and "not" in red vs. not) clearly indicate Stroop modulation both within and between experiments.

The results of Experiment 2 extend the hypothesis of the role of mental set as presented by Besner and Stolz, (1999). Besner and Stolz argue that the stimulus characteristics of their version of the Stroop task prompted participants to separate the Stroop stimulus into separate perceptual objects (e.g., processing at the level of the single letter rather than the whole word). The disjoining of the color and semantic information led to a reduction in Stroop interference. In other words, the task and stimulus characteristics engendered a mental set that led to bypassing the "otherwise automatic" involuntary action of reading the Stroop word. With the decreasing likelihood that the Stroop word would be read, the potential for Stroop interference was similarly reduced.

General Discussion

The basic question of the present experiments concerns the effect of the stimulus characteristics' change in response set on Stroop processing. Rather than manipulating

the stimulus itself, the whole experimental manipulation was designed to be restricted to a cognitive recoding of the response properties rather than a gross manipulation of the stimulus materials themselves.

In the current experiments participants made fewer Task 2 errors in Experiment 2 than in Experiment 1. This strongly suggests that the task in Experiment 2 was easier. The most parsimonious explanation for this effect is that the strength of association between the competing stimulus characteristics and their appropriate response was stronger in Experiment 1 than in Experiment 2. The decades of research on Stroop suggest that the processing underlying Stroop interference is initially triggered by the stimulus itself and cannot be interfered with by other mental activities. Naively then, one might suggest that the data produced by the tasks in Experiments 1 and 2 would be the same. Why does it increase accuracy rate on Experiment 2? In the introduction two possible accounts were presented. The first is the *speed-of-processing* model; the second is the *strength-of-association* model.

As mentioned in the introduction, the relative speed-of-processing model contains three key assumptions. They are: parallel processing of the two dimensions of the stimulus at differential speeds, a limited-capacity response channel into which only one of the two potential responses can be accepted at a time, and the potential response must receive input from several different sources, including preceding trials and other response-set elements. Explicit manipulations that ought to have differentially manipulated color-based and word-based processing led us to reject the speed-of-processing model (MacLeod, 1991).

A second alternative, and the one in which the author interprets the current data, is a strength-of-association model. The strength-of-association model highlights the theoretical importance of the strength of the stimulus-response relationship between the different aspects of the Stroop stimulus such as the physical color and the word on the stimulus side as well as the verbal or button press response on the response side. Stroop interference varies on a continuum as a function of the semantic association between the stimulus and the response. When the distractor element of the Stroop item is the same as the non-desired response (e.g., RED-GREEN Task), it is more strongly associated with the interfering response than when the distractor element of the Stroop item is not the same as the non-desired response (e.g., RED-NOT RED Task). Thus, both stimulus and response set manipulations can induce a gradient of semantic-based interference. Once a semantic representation of the distractor word is activated, the degree of association between this semantic representation and the incongruent response will modulate the amount of interference. The current set of experiments provides evidence consistent with the strength-of-association model with respect to the manipulation of response set.

The additional analyses performed on the data from Experiments 1 and 2 illustrated that when looking at the amount of interference produced by the incongruent conditions, the amount of interference depended heavily on response set. In the RED-GREEN Task, the congruent versus incongruent difference did not differ by response. In the RED-NOT Task, the “not” responses showed negligible differences across the characteristics’ change in response set on Stroop processing. Rather than manipulating

congruency manipulation whereas the “red” responses still reflected a substantial congruency effect.

According to Coles et al. (1985), color and verbal processing are relatively independent of each and follow separate paths; the former must be complete before the latter is repressed to avoid response competition. As each is processing its part of the stimulus, it is also priming a response. When a preset priming threshold is reached, a response occurs. According to this hypothesis, Stroop interference is a result of the additional time needed to suppress the incorrect verbal response. This idea undermines the theoretical claim that automaticity is not subject to interference from other mental activities since the response set has been demonstrated to powerfully modulate Stroop interference. The reduction of Stroop interference in the present study, will be argued to reflect a reduction in S-R association rather than manipulating the automaticity of processing.

What did we gain from using the PRP paradigm? In both experiments the Stroop task took place within the context of being the second of two tasks in a PRP paradigm. Prior use of the Stroop task in PRP paradigms has shown that the magnitude of Stroop interference is not affected by the time between the onset of the stimulus for Task 1 and the onset of the stimulus for Task 2. In technical terms, Stroop interference is additive with SOA. Consistent with this, the author fails to pick up a significant interaction between Congruency and SOA in each of Experiment 1 and 2 as well as when analyzing their data jointly, $F < 1$. The implication of this result is that the stability of the additivity of congruency across SOA is consistent with the results previously found

for “typical” stroop processing despite the author’s use of a two-color stroop task and the response set manipulation. This provides evidence that the processing in the RED-NOT task is, at the very least, substantively similar to “normal” Stroop processing.

Stroop effects are complex and diverse, and it seems clear that a broad unifying theory to account for Stroop Effects must include a more encompassing set of parameters than the now-discounted speed-of-processing or other simplistic models have typically included. A comprehensive theory should encompass the interactions of various cognitive subsystems in its presentation of the causes of Stroop interference. As the current experiments show, some of the robust automatic reading processes can be interfered with via instructional manipulations rather than a direct manipulation of the stimulus properties. This work may encourage future attempts to understand the response underlying processes by explicitly advocating for the inclusion of both stimulus and based inputs into predictions of Stroop interference.

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Appendix
Signed Approval Form

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To: Tao-Chung Wang
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From: Pam Stacks, AVP
Graduate Studies & Research

Date: October 26, 2005

The Human Subjects-Institutional Review Board has approved your request to use human subjects in the study entitled:

“The Role of Colors and Response Mechanisms.”

This approval is contingent upon the subjects participating in your research project being appropriately protected from risk. This includes the protection of the anonymity of the subjects' identity when they participate in your research project, and with regard to all data that may be collected from the subjects. The approval includes continued monitoring of your research by the Board to assure that the subjects are being adequately and properly protected from such risks. If at any time a subject becomes injured or complains of injury, you must notify Pam Stacks, Ph.D. immediately. Injury includes but is not limited to bodily harm, psychological trauma, and release of potentially damaging personal information. This approval for the human subjects portion of your project is in effect for one year, and data collection beyond October 26, 2006 requires an extension request.

Please also be advised that all subjects need to be fully informed and aware that their participation in your research project is voluntary, and that he or she may withdraw from the project at any time. Further, a subject's participation, refusal to participate, or withdrawal will not affect any services that the subject is receiving or will receive at the institution in which the research is being conducted.

If you have any questions, please contact me at (408) 924-2480.

Cc: Dr. Mark Van Selst