31 Response features in the coordination of perception and action

Gordon D. Logan and N. Jane Zbrodoff

Abstract. Theories of congruency effects in Stroop, Simon, and S–R compatibility tasks often start with a node that represents a stimulus category and end with a node that represents a response category. We ask how a stimulus can activate a node and how a node can activate a response and suggest that congruency effects may stem from these prior and subsequent processes. Theories of word recognition propose several interacting stages between stimulus presentation and activation of a word node. Theories of speaking and typing propose several interacting stages between activation of a word node and the execution of a response. We focus on the response end, and show that the Stroop effect depends on individual features of the response 'downstream' from the response node. We show that the time for a vocal response depends on the specific phonemes that are activated by the Stroop distractor, whereas the time for a typewritten response depends on the specific finger movements that are evoked by the Stroop distractor. These results call for a theory of congruency effects that links current theories of word recognition with current theories of speaking and typing. Congruency effects may reflect stimulus-driven interactions among response features.

31.1 Introduction

If William James were alive today, he would probably say, 'Everyone knows what the Stroop (1935) effect is.' It is the interference observed in the time to name colors that is produced by distracting words that name incongruent colors (e.g. RED printed in green). It is defined relative to neutral (e.g. XXX in green) or congruent (e.g. GREEN in green) control conditions. It has been replicated hundreds of times for hundreds of reasons (for a review, see MacLeod 1991), but many important aspects of the effect remain unexplained. The purpose of this chapter is to add constraints to the explanation provided by dominant theories of the Stroop effect (Cohen, Dunbar, and McClelland 1990; Logan 1980; Logan and Zbrodoff 1979), suggesting ways in which the theories can be extended. We argue that the Stroop literature is relatively insular and could benefit by incorporating ideas and theories from other parts of cognitive psychology. Specifically, we show that the Stroop effect depends on detailed features of the motor response, which indicates a locus of the effect that is much farther 'downstream' than the dominant theories suggest. We use theories of speaking (Dell 1986) and typing (Rumelhart and Norman 1982) to define the parts further downstream and suggest ways to incorporate those theories into theories of the Stroop effect.

We are not the first to make these points. Indeed, several studies in the Stroop literature show evidence of effects downstream (Bakan and Alperson 1967; Besner, Stolz, and Boutilier 1997; Cutting and Ferreira 1999; Dalrymple-Alford 1972; Dennis and Newstead 1981; Guttentag and Haith 1978; Klein 1964; Logan and Zbrodoff 1998; Majeres 1974; McClain 1983; Melara and Mounts 1993; Pritchatt 1968; Proctor 1978; Redding and Gerjets 1977; Regan 1978; Singer, Lappin, and Moore 1975; Tannenhaus, Flanigan, and Seidenberg 1980; Virzi and Egeth 1985). We discuss these studies in more detail later in the chapter. Several studies outside the Stroop literature show Stroop-like effects downstream as well. Greenwald (1970, 1971, 1972) manipulated the match between stimulus and response modalities and found strong effects in single- and dual-task conditions. Meyer and Gordon (1985; Gordon and Meyer 1987) found syllable-specific priming effects in speech production. Posnansky and Rayner (1977) and Rayner and Springer (1986) found Stroop-like interference between phonemes in a picture–word interference task. Indeed, theories of picture–word interference (e.g. Glaser and Glaser 1989) and speech production (e.g. Levelt *et al.* 1991) exploit effects upstream and downstream from the current Stroop theories to great advantage. However, the points made by these researchers have not been incorporated into the dominant theories of the Stroop effect, so it is worth repeating them and elaborating them in the context of the Stroop effect.

31.2 Reading, speaking, and theories of the Stroop task

Two prominent theories of the Stroop task are depicted in Fig. 31.1. Panel A presents our model from 1979 and 1980 and Panel B presents the Cohen *et al.* (1990) model. In the figure and throughout the chapter, colors are represented as lower-case words like red and green, words are represented as uppercase words like RED and GREEN, and responses are represented as words in quotes like ‘red’ and ‘green’. The models in Fig. 31.1 are not the only models in the Stroop literature (see e.g. Phaf, Van der Heijden, and Hudson 1990; Sugg and McDonald 1994; Virzi and Egeth 1985; Zhang, Zhang, and Kornblum 1999) but they provide the most complete account of the data (MacLeod 1991). More importantly, they share a critical assumption with most of the other models of Stroop, Simon, and compatibility effects: *stimulus and response categories can be represented as single nodes in a localist network*. The input to each of the models is the activation of a node representing the attributes of the current stimulus. In the single-trial version of the Stroop task, each stimulus activates two input nodes, one for the word and one for the color. The output from each of the models is a response node that is activated above some threshold. On *congruent* trials (e.g. RED in red), the two attributes activate the same response node and that speeds reaction time (RT) relative to neutral control conditions. On *incongruent* trials (e.g. GREEN in red), the two attributes activate different response nodes and that creates competition between the response nodes that increases the time it takes for the winning node to reach the threshold.

31.2.1 How can a node read?

The Stroop models presented in Fig. 31.1 beg an important question: How does a stimulus turn on a node? Many careers have been built on studying the processes by which colors are categorized and words are read. The processes by which the stimulus turns on nodes that represent categorizations of its attributes are multiple and complex. Considerable progress was made in the last century, resulting in a series of models of increasing complexity that account for an increasingly broad range of empirical phenomena (see, e.g. Coltheart, Curtis, Atkins, and Haller 1993; Harm and Seidenberg 1999; McClelland and Rumelhart 1981). We present some examples of word-reading models in Fig. 31.2 to illustrate the complexity of the processes ‘upstream’ from the input nodes in the Stroop models in Fig. 31.1. They show that reading generates outputs at several levels that may interact with the process of naming a color. For example, phonological or semantic codes or both may cause

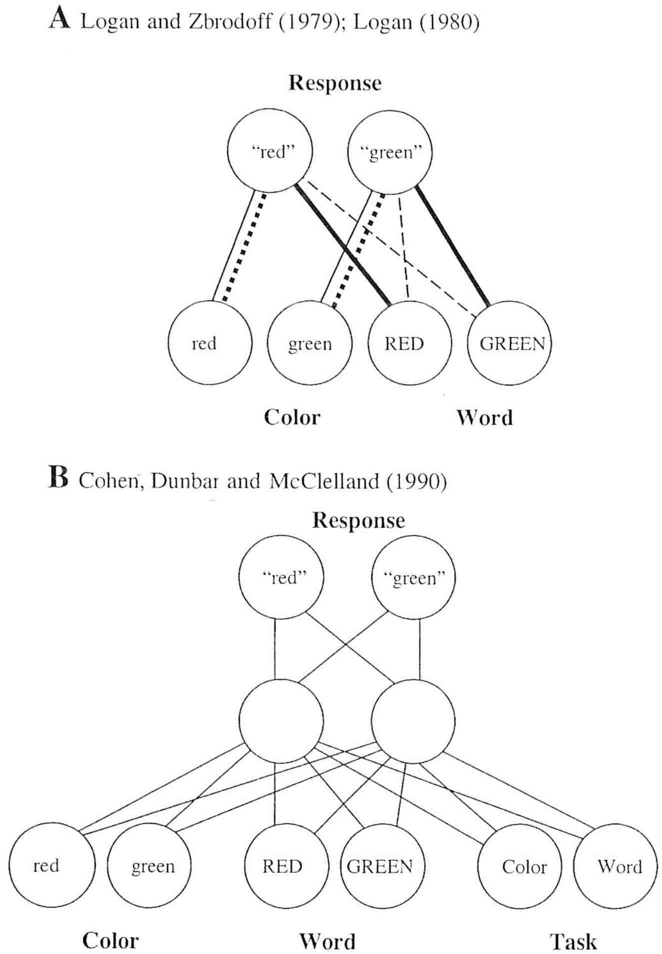

Fig. 31.1 The currently dominant models of the Stroop effect according to MacLeod (1991). *Panel A* presents the information accumulation model of Logan and Zbrodoff (1979) and Logan (1980). The circles represent nodes and the lines represent connections between them. Solid lines represent long-term automatic connections. Broken lines represent short-term attentional connections. The thickness of the line represents the strength of the connection. Automatic connections are stronger between words and responses than between colors and responses, representing the greater automaticity of word reading. Attentional connections are stronger between colors and responses than between words and responses to allow the system to respond to color. Attentional connections between words and responses are reversed so the system is set to expect incongruent trials. *Panel B* presents the parallel-distributed-processing model of Cohen, Dunbar, and McClelland (1990). The circles represent nodes and the lines represent connections between them. Connection strength is not represented in this picture of the model but varies depending on the model's experience in the simulations. The Word and Color nodes in the bottom right are 'task demand units' that set the system to report words or colors, depending on which node is activated.

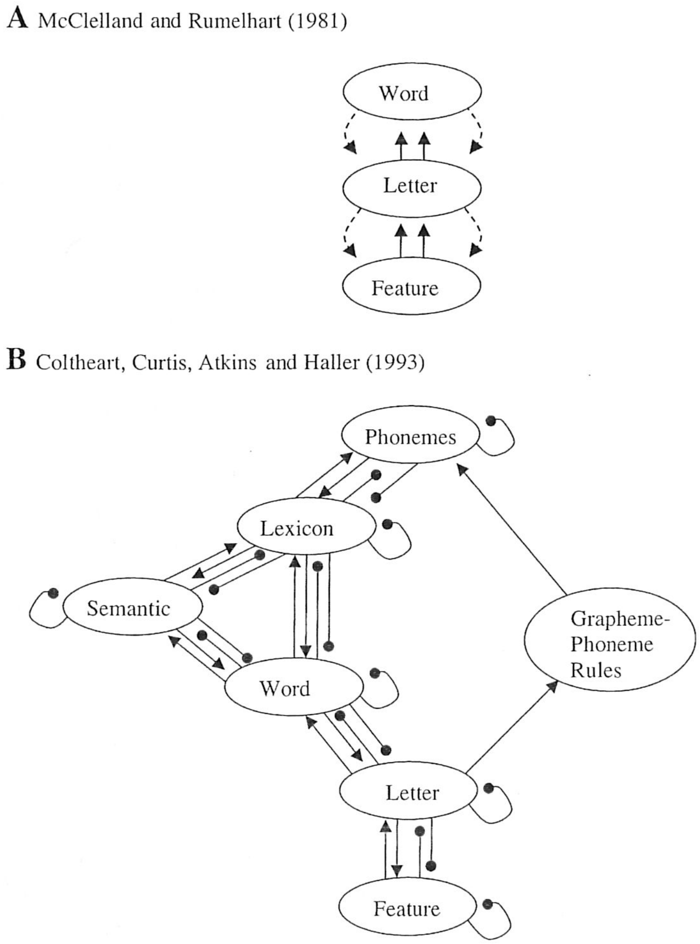

Fig. 31.2 Two models of word recognition. *Panel A* presents the interactive activation model of McClelland and Rumelhart (1981). The ovals represent sets of nodes of particular types. Nodes within ovals are mutually inhibitory. The lines represent connections between nodes of different types. The number of lines in this picture does not represent the number of connections in the simulation model. Arrowheads represent the direction in which activation flows. Solid lines represent bottom-up activation. Broken lines represent top-down activation. *Panel B* presents the dual route model of Coltheart *et al.* (1993). The ovals represent collections of nodes and the lines represent connections between them. The arrowheads and dots represent the direction along which activation flows. Arrowheads represent excitatory connections and dots represent inhibitory connections. The input consists of visual features and the output is a phonetic description of the word, ready to be input to a speaking model. The branch on the right side represents the phonological route, in which pronunications are derived by applying grapheme-to-phoneme correspondence rules. The branch on the left side represents the visual route, in which pronunciations are derived through a sequence of steps that begins with recognizing words.

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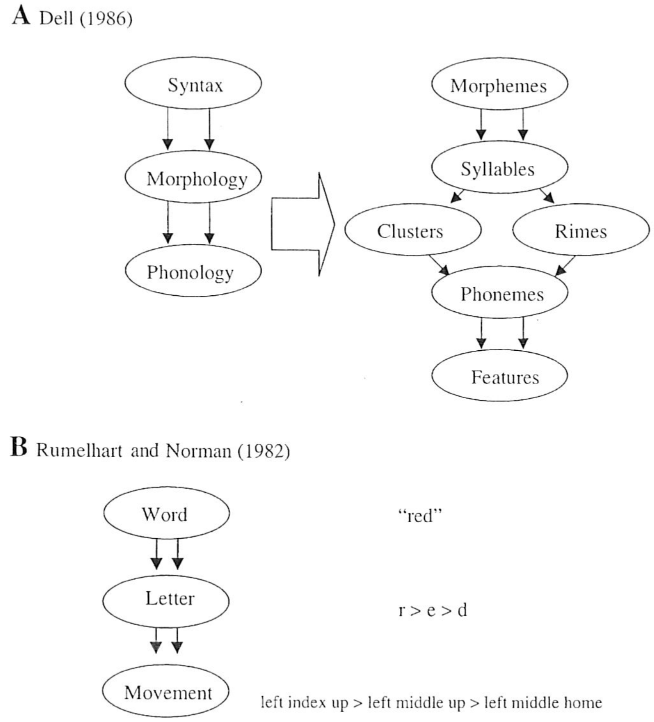

Fig. 31.3 Models of speaking and typing. *Panel A* presents the spreading activation retrieval model of speaking by Dell (1986). The left side shows activation flow through three main stages. Syntax orders the words, Morphology chooses the word forms, and Phonology translates the words into vocal gestures. The right side shows a more detailed model of the activation flow from morphology to phonology—from word to utterance. *Panel B* presents the schema activation model of typing by Rumelhart and Norman (1982). The left side shows activation flow through three main stages. Word takes input from ideational or perceptual processes, Letter translates words into constituent letters, and Movement translates letters into movements of the hands and fingers. The right side shows the word 'red' cascading through the model, first broken into a sequence of letters, then into a sequence of movements.

interference. Thus, some of the Stroop effect may be produced by processes prior to those depicted in the Stroop models in Fig. 31.1. The theories may have to be extended to account for them.

31.2.2 How can a node speak?

The Stroop models in Fig. 31.1 beg another important question: how can an active response node cause the series of events that unfolds when people speak or type a color name? Figure 31.3 contains a prominent model of speech production by Dell (1986) and a prominent model of typewriting by Rumelhart and Norman (1982). The input to each model is a word, which may be an activated response node in a Stroop model. The words are transformed into constituents (syllables in speaking;

letters in typing) and those constituents are transformed into smaller constituents—vocal gestures in speaking and finger movements in typing. Moreover, each model must solve the emergent problem of serially ordering the constituents at each stage of processing.

The models in Fig. 31.3 illustrate the complexity of the processes downstream from the output nodes in the Stroop models (also see Levelt *et al.* 1991). As with the upstream processes, the downstream processes present several loci at which word reading may interfere with color naming. With vocal responses, there may be competition between words, between syllables, between phonemes, or between some combination of them. With typewritten responses, there may be competition between words, letters, and movements. Each of these loci could produce interference that contributes to the Stroop effect. As with reading, these downstream processes are outside the dominant Stroop models depicted in Fig. 31.1. Should the effects exist, the Stroop models would have to be extended to account for them.

31.2.3 What happens when nodes read aloud?

It would be very interesting to put the models of reading in Fig. 31.2 together with the models of speaking and typing in Fig. 31.3 (for a similar suggestion, see Coltheart *et al.* 1993). The resulting model would provide a complete account of reading aloud, from print to sound. It would be interesting as well to apply the resulting model to the Stroop effect. It may turn out that the combined model would account for the Stroop effect without having to add the processes that intervene between stimulus nodes and response nodes in the Stroop models. Alternatively, the combined model may need features of the Stroop models to account for the Stroop effect. These intriguing questions await future research.

The goal of the research reported in this chapter was to take a step toward this ultimate goal by demonstrating the contribution of response features downstream from the Stroop models to the Stroop effect. If we can show that response features modulate the Stroop effect, we will have shown that the dominant Stroop models are insufficient and must be extended to provide a more detailed account of the downstream processes.

31.3 Response features and the Stroop task

31.3.1 Response type effects

One piece of evidence for a downstream locus of the Stroop effect comes from studies of response type effects. The dominant Stroop theories represent responses as abstract categories. Nothing in the nodes distinguishes between vocal and manual responses, for example. Several researchers have shown that the magnitude of the Stroop effect depends on the nature of the response. Stroop effects are smaller with manual (arbitrary keypress) responses than with the standard vocal responses (e.g. Logan and Zbrodoff 1998; Majeres 1974; McClain 1983; Melara and Mounts 1993; Pritchatt 1968; Redding and Gergets 1977; Virzi and Egeth 1985). This is not a response modality effect (cf. Virzi and Egeth 1985), because skilled manual responses (typewriting) can produce larger Stroop effects than vocal responses (Logan and Zbrodoff 1998). Instead, response type effects seem to reflect the match or compatibility of the stimulus categories and the response categories: words map more naturally onto spoken and typewritten responses than onto arbitrary keypresses.

Response type interacts strongly with the judgment required for the Stroop task (Majeres 1974; Virzi and Egeth 1985). One of our unpublished studies illustrates the interaction. We showed subjects the words ABOVE, BELOW, LEFT, and RIGHT, above, below, left of, and right of the fixation point, and had them report the word or the location. We used all possible combinations of words and locations, and three different response types: vocal responses, arbitrary keypresses, and compatibly mapped responses on the numeric keypad (i.e. 8 for above, 2 for below, 4 for left, and 2 for right). When subjects reported the word, the congruency effects were 7, 31, and 109 ms for vocal, arbitrary keypress, and keypad responses, respectively. When subjects reported the location, the pattern of effects was reversed. The congruency effects were 61, 43, and 29 ms for vocal, arbitrary keypress, and keypad responses, respectively.

These effects show that the nature of the response makes a difference in the Stroop task. The data are consistent with the idea that the effect occurs downstream from the dominant Stroop theories, but they are also consistent with other ideas. It may be possible to account for the response type effects in terms of strength of connections between stimulus nodes and response nodes in the dominant theories (Cohen *et al.* 1990; Logan 1980; Logan and Zbrodoff 1979).

31.3.2 Response similarity effects

Another piece of evidence that suggests a downstream locus of the Stroop effect comes from studies that manipulate the similarity between distractors and the responses required for the task. Several investigators showed that the magnitude of the Stroop effect depends on the similarity of the distractors to words in the set of response categories. Distractors that are outside of the response set produce smaller Stroop effects. Words that name colors produce less interference if they are not in the response set. For example, if subjects see red and green words but not blue and yellow ones, and the task is to say what colour the word is, then 'red' and 'green' are in the response set and 'blue' and 'yellow' are not. RED in green will produce more interference than BLUE in green (Klein 1964; Proctor 1978).

One of our unpublished experiments illustrates response set effects in a different way. We presented words in four colors (red, blue, green, and yellow) in four locations (above, below, left of, or right of fixation) and had subjects report either the color or the location. There were eight distractor words: four color names (RED, BLUE, GREEN, and YELLOW) and four location names (ABOVE, BELOW, LEFT, and RIGHT). All combinations of colors, locations, and words occurred equally often. This design provided two kinds of congruency effects: color congruency between the color and the color words and location congruency between the location and the location words. Location words were neutral with respect to color naming; they were outside the response set. Color words were neutral with respect to location naming, outside the response set.

The results showed strong congruency effects that depended on subjects' response set: when subjects reported color, there was a strong color congruency effect (132 ms) and virtually no location congruency effect (−5 ms). When subjects reported location, the pattern reversed. The location congruency effect was strong (54 ms) and the color congruency effect was weak (−8 ms). Stimulus conditions were the same in the two report conditions. All that changed was the nature of the response, and that determined the pattern of the congruency effects. Put differently, these results show that congruency between stimulus properties is not in itself sufficient to produce a Stroop effect. The congruency between stimulus properties and response properties seems necessary.[1]

Stimuli outside the response set produce smaller Stroop effects, but the magnitude of the effects they produce depends on similarity to the words in the response set. Words semantically associated with color (e.g. SKY, GRASS) produce less interference than color names but more interference than words that are not associated with color (Dalrymple-Alford 1972; Klein 1964; Majeres 1974; Regan 1978). Letters from color words produce a smaller Stroop effect than color words (Redding and Gerjets 1977; Regan 1978; Singer *et al.* 1975; also see Besner *et al.* 1997).

These effects could be due to processes downstream from the dominant Stroop theories. They could reflect the activation of nodes after the words (e.g. syllables, phonemes, and features in speaking; letters and movements in typing; see Fig. 31.3). However, the effects could also be due to processes that are already part of the dominant Stroop theories. Color words outside the response set may activate responses that do not compete with correct responses. Semantically related words may partially activate the color words in the response set.

Some researchers manipulated the phonological similarity of distractors. Pronounceable non-words produce a stronger Stroop effect than unpronounceable controls (Bakan and Alperson 1967; Guttentag and Haith 1978). Distractors that sound like color words produce a stronger Stroop effect as well (Dennis and Newstead 1981; also see Cutting and Ferreira 1999; Tannenhaus *et al.* 1980). These effects are more plausible candidates for a locus downstream from the dominant Stroop theories because the similarity is between the constituents of words rather than words themselves. Still, an advocate of a dominant theory could argue that the effects reflect partial activation at word-level nodes rather than interference in downstream nodes (syllables, phonemes, or features in speech; letters or movements in typing).

31.4 The present experiments

The present experiments were designed to find more direct evidence for Stroop effects downstream from the dominant theories. We manipulated distractor similarity by varying the type of distractor, presenting words that name colors on some trials (e.g. RED, GREEN) and repetitions of the first letters of words that name colors on others (e.g. RRR, GGGGG). To show that this manipulation affected processes downstream, we manipulated response type and response set. In Experiment 1, subjects responded vocally. Half of the subjects responded by saying the color name (e.g. 'red' for red) and half responded by saying the first letter of the color name (e.g. 'r' for red). In Experiment 2, subjects responded by typing the color name. Majeres (1974) performed similar experiments using the original list format Stroop task (presenting 40 colored stimuli and measuring the time to name all of them). We used the single-trial version of the task.

We expected that word distractors would activate color name responses and letter distractors would activate letter name responses. Color names and letter names should interact with response set (saying words or saying letters), producing stronger congruency effects when they correspond than when they do not. Color names and letter names should interact differently with spoken and typed responses because they differ in different ways at the level of constituents (syllables, phonemes and features in speech; letters and movements in typing). Across experiments, we expected an interaction between distractor type, response set, response type, and congruity such that the magnitude of the Stroop effect depends on the downstream properties of the response evoked by the distractor. The Stroop effect should be larger with word distractors than with letter distractors with color words as responses (Experiment 1), but not with single letters (Experiment 1) or typewritten words (Experiment 2) as responses. Our argument rests on this higher order interaction. Lower order interactions may be ambiguous, interpretable in terms of the dominant theories as well as interpretable as downstream effects. The higher order interaction is unambiguous. If it comes out as predicted, it may resolve some of the ambiguity in the lower order interactions.

31.5 Experiment 1: word and letter distractors with vocal responses

The first experiment looked for an interaction between distractor type, response set, and congruity with vocal responses. We expected the Stroop effect to be smaller with letter distractors than with words when subjects named the whole word because the letters are less similar to the required words phonetically. The difference in similarity can be seen in the phonetic transcriptions for color names and first letters of color names that appear in Table 31.1. The letters are not pronounced like the words and so should produce less interference at the phonetic and feature levels.

The difference in interference should reverse or at least be less prominent when subjects respond by saying the first letter of the color name. Letter distractors should activate responses relevant to the task at the phonetic and feature levels and so should produce a stronger Stroop effect. Word distractors should activate irrelevant word responses and so should produce a weaker Stroop effect. However, subjects may perform the task by first retrieving the color name and then retrieving the first letter from the color name. In that case, word distractors may interfere with the first step and letter distractors may interfere with the second step. Word and letter distractors may produce the same amount of interference. Regardless of this, the pattern should be different from that observed when subjects respond by saying the whole color word; there should be a significant interaction between distractor type, response set, and congruency.

31.5.1.1 Method

Subjects. The subjects were 32 undergraduate students. Some served for credit in an Introductory Psychology course. Others served for $6.00 US.

Apparatus and stimuli. The stimuli were the words RED, GREEN, BLUE, and YELLOW and the letter strings RRR, GGGGG, BBBB, and YYYYYY. They were presented in red, green, blue, and yellow (IBM colors 12, 10, 9, and 14, respectively) on a black background (IBM color 0) on Gateway2000 monitors controlled by Gateway2000 486 computers. The stimuli were presented in the center of the screen. Viewed at a distance of 60 cm, they subtended 0.48 deg of visual angle vertically. The horizontal visual angles were 0.95 deg for RED and RRR, 1.24 deg for BLUE and BBBB, 1.53 deg for GREEN and GGGGG, and 1.81 deg for YELLOW and YYYYYY.

Each trial involved a series of three displays. The first was a fixation display containing a + sign centered in the screen (row 12, column 40 in the standard 24 row × 80 column IBM text screen) that

Table 31.1 Phonetic transcriptions of color names and first letters of color names

Color word	*Phonetic transcription*	*Letter*	*Phonetic transcription*
'red'	[rɛd]	'r'	[⊃r]
'blue'	[blue]	'b'	[bi]
'green'	[grin]	'g'	[ji]
'yellow'	[yɛl ow]	'y'	[way]

was exposed for 500 ms. The fixation display was extinguished and replaced immediately by the imperative stimulus for that trial (a colored word or a colored letter string), which was left-justified two spaces to the left of the fixation point (i.e. it began on row 12, column 38 of the text screen). The imperative stimulus remained exposed until the subject responded, whereupon the screen went blank. The experimenter, who was present in the room, then typed in the subject's response. When the experimenter's response was registered, a 1000 ms intertrial interval began during which the screen remained blank.

Procedure. The basic design of the experiment involved 32 trials formed by the factorial combination of two distractor types (word or letter), four distractors (the four color words, RED, BLUE, GREEN, and YELLOW, or the four strings of first letters, RRR, BBBB, GGGGG, and YYYYYY), and four colors (red, blue, green, and yellow). The basic design was replicated 16 times for a total of 512 trials. The different combinations of conditions were presented in a different random order for each subject. Subjects were allowed short breaks every 64 trials.

Subjects were told to respond vocally to the color and ignore the distractor. They were told to respond as quickly as possible without making errors. Half of the subjects were told to say the whole color name (e.g. 'red' for red) and half were told to say just the first letter of the color name (e.g. 'r' for red). Subjects were tested individually. The experimenter was present throughout the session. She typed the subject's response into the computer so we could check accuracy.

31.5.1.2 Results

We analyzed the RT and accuracy data in 2 (distractor type: word vs. letter) × 2 (response set: word vs. first letter) × 2 (congruency) analyses of variance (ANOVAs). The mean RTs and accuracy scores for each cell of the design are presented in Table 31.2. The mean RTs for the critical interaction between distractor type, response set, and congruency are plotted in Fig. 31.4. The RTs are converted to congruency scores (incongruent RT—congruent RT) to illustrate the interaction more clearly.

RT was 22 ms faster with letter distractors than with word distractors, $F(1, 30) = 33.43$, $p < 0.01$, $MSE = 457.20$, 106 ms faster with words responses than with first-letter responses, $F(1, 30) = 9.81$, $p < 0.01$, $MSE = 37029.96$, and 78 ms faster with congruent distractors than with incongruent distractors, $F(1, 30) = 77.04$, $p < 0.01$, $MSE = 2468.63$. These effects were qualified by several interactions. The most important was the highest order interaction between distractor type, response set, and congruency, $F(1, 30) = 4.43$, $p < 0.05$, $MSE = 697.49$. It is plotted in Fig. 31.4.

Table 31.2 Mean reaction times in ms and accuracy scores (percent correct, in parentheses) for vocal responses as a function of distractor type (words vs. repetitions of first letter), response set (say color name vs. first letter of color name), and congruency in Experiment 1

Distractor	*Say word*		*Say first letter*	
	Word	*First letter*	*Word*	*First letter*
Incongruent	718 (95)	663 (97)	801 (95)	724 (94)
Congruent	612 (98)	605 (99)	724 (96)	660 (97)
Stroop effect	106 (3)	58 (2)	77 (1)	64 (3)

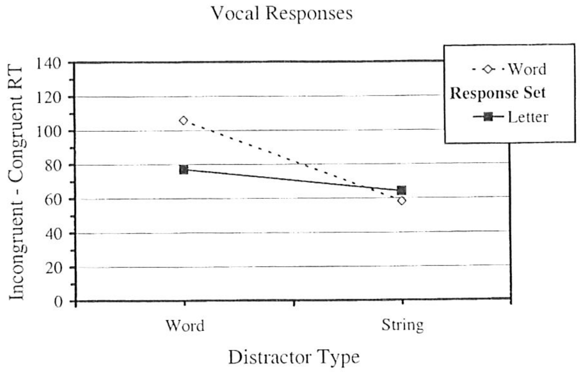

Fig. 31.4 Congruency effects as a function of distractor type and response set in Experiment 1, in which responses were vocal.

The distractor type × response set × congruency interaction indicates that the congruency effect was modulated by distractor type with whole word responses but not with first-letter responses. The modulation of the congruency effect with whole word responses was predicted by our analysis: whole word distractors should activate morphological, phonological, and featural levels in common with the response set and so should produce a large Stroop effect. Repeated letter distractors should not activate word responses at any level, though they may cause partial activation. The Stroop effect should therefore be smaller, as we observed. A contrast comparing the difference in congruency effects was highly significant, $F(1, 30) = 26.43$, $p < 0.01$, $MSE = 697.49$.

The constancy of the congruency effect with first letter responses was also predicted. Subjects may have generated color names to determine which letter to say. RT was 106 ms longer to say letters than to say words, consistent with the idea that subjects generated color names. Word distractors may interfere with generation of color names while letter distractors interfere with generation of letter names, resulting in equivalent congruency effects. A contrast comparing the difference in congruency effects was not significant, $F(1, 30) < 1.0$.

In the RT analysis, there were significant interactions between distractor type and response set, $F(1, 30) = 6.11$, $p < 0.05$, $MSE = 457.20$, and distractor type and congruency, $F(1, 30) = 8.93$, $p < 0.01$, $MSE = 697.49$. The meaning of these interactions is qualified by the higher order interaction between distractor type, response set, and congruency.

The accuracy data corroborated the RT data. Accuracy was lower when RT was longer, suggesting no trade-off between speed and accuracy. The accuracy ANOVA revealed significant main effects of distractor type, $F(1, 30) = 5.53$, $p < 0.05$, $MSE = 2.65$, response set, $F(1, 30) = 6.15$, $p < 0.05$, $MSE = 14.47$, and congruency, $F(1, 30) = 17.03$, $p < 0.01$, $MSE = 7.95$, and a significant three-way interaction between distractor type, response set, and congruency, $F(1, 30) = 6.70$, $p < 0.05$, $MSE = 3.19$. The interaction between distractor type and response set approached significance, $F(1, 30) = 4.00$, $p < 0.06$, $MSE = 2.65$.

31.5.1.3 Discussion

The experiment showed a Stroop effect that was modulated by distractor type and response type. When subjects responded by saying the whole word, the Stroop effect was almost twice as strong with word distractors as with letter distractors. When subjects responded by saying the first letter of the word, the Stroop effect was about the same for word and letter distractors. These results are consistent with the idea that the Stroop effect occurs downstream from the dominant theories, in phonological and featural levels of processing. Word distractors activate the phonemes and features of words, whereas letter distractors activate the phonemes and features of letters. The activated phonemes and features have an impact on performance that depends on their similarity to the set of intended responses. Word distractors are more similar to word responses than letter distractors are (see Table 31.1) and so produce a stronger Stroop effect with word responses, just as we observed. Letter distractors are more similar to letter responses than word distractors are, and so tend to produce a stronger Stroop effect with letter responses. Subjects appeared to generate letter responses by first generating the words that name the colors, and word distractors may interfere more with that process more than letter distractors do. Putting the two effects together results in equivalent Stroop effects for word and letter distractors, as we observed with letter responses.

These results are consistent with a downstream locus for the Stroop effect but they are also consistent with a locus within the dominant Stroop theories. Words may interfere more with word responses because they activate word responses more than letters do. Letters may interfere more with letter responses because they activate letter responses more than words do. The additional step of retrieving the color name before getting the first letter may suffer more interference at the word level. Downstream constituents need not be invoked to explain our results. Consequently, we ran a second experiment to obtain converging evidence on our conclusions.

31.6 Experiment 2: word and letter distractors with typewritten responses

The second experiment was a replication of the whole-word response condition of the first experiment with typewritten responses instead of vocal responses. Subjects saw colored color words and colored repetitions of the first letter of color words and had to name the color by typing the whole color word. We expected the pattern of results to be different from the one we observed with whole-word vocal responses because words and letters relate to each other differently in typing and speaking. Letters are the constituents of typed words but they are not the constituents of spoken words: syllables and phonemes are instead. With typewritten responses, word distractors and letter distractors activate the same initial movement: 'r' is typed the same way whether it is the first letter of the word RED or the single letter R. By contrast, with vocal responses, word distractors and letter distractors activate very different initial movements (see Table 31.1). Consequently, we expected the Stroop effect to be the same magnitude for word and letter distractors when subjects typed whole words.

This prediction is based on the idea that the Stroop effect occurs at the letter level or the movement level. At the level of responses (word vs. letter responses), words and letters do not resemble each other. If the Stroop effect depended on responses rather than the constituents of the responses, the pattern of results observed in Experiment 1 should replicate here. Words should interfere more than letters.

The crucial prediction is a null interaction (the magnitude of the Stroop effect should be the same with word and letter distractors) and that is weaker than predicting a significant effect. We strengthen the prediction by comparing RTs in the word response condition in Experiment 2 with RTs in the word response condition in Experiment 1 in a 2 (Experiments: 1 vs. 2) $\times$ 2 (distractor type: word vs.

letter) × 2 (congruency) ANOVA. The crucial prediction is an interaction between experiments, distractor type, and congruency of the following form: the Stroop effect should be larger with word distractors than with letter distractors when subjects speak the color name (Experiment 1) than when they type the color name (Experiment 2).

31.6.1.1 Method

Subjects. The subjects were 16 graduate and undergraduate students who were selected for their ability to touch type. They were paid $6 for participating. The average speed on Logan and Zbrodoff's (1998) typing test was 48.7 words per minute with a range of 38.5 to 81.1 words per minute. The average accuracy on the typing test was 89.5% with a range of 81% to 97%.

Apparatus and stimuli. These were the same as in the previous experiment, except that subjects registered their responses by typing on the computer keyboard rather than speaking. The typing test involved typing one of four paragraphs from the appendix of Logan and Zbrodoff (1998, p. 992), which were adapted from the book *Border collies* by Collier (1995). The paragraphs ranged in length from 111 to 117 words. The text was displayed on the computer's monitor. Subjects read through the text once without typing it to familiarize themselves with the text before they typed it. During typing, the text remained on the screen, but the characters that were typed were not echoed on the screen. Some subjects would have preferred to see what they typed, so their typing speeds on our test may underestimate their true ability.

Procedure. The procedure was the same as in the previous experiment except that subjects responded by typing rather than speaking and all of the subjects typed the word representing the color name.

31.6.1.2 Results

We analyzed the RT and accuracy data in 2 (distractor type: word vs. letter) × 2 (congruency) ANOVAs. The mean RTs and accuracy scores are presented in Table 31.3.

RT was 45 ms faster with letter distractors than with word distractors, $F(1, 15) = 39.81$, $p < 0.01$, $MSE = 801.59$, and 95 ms faster with congruent distractors than with incongruent distractors, $F(1, 15) = 68.67$, $p < 0.01$, $MSE = 2073.60$. The interaction between distractor type and congruency was not significant, $F(1, 15) < 1.0$. Word distractors produced a 99-ms congruency effect while letter distractors produced a 90-ms congruency effect.

The null interaction between distractor type and congruency is consistent with our predictions. To strengthen the result, we compared the present RT data with RT data from the whole word response condition of Experiment 1 in a 2 (Experiments) × 2 (distractor type) × 2 (congruency) ANOVA. The

Table 31.3 Mean reaction times in ms and accuracy scores (percent correct, in parentheses) for typewritten responses as a function of distractor type (words vs. repetitions of first letter) and congruency in Experiment 2

Distractor	*Word*	*First letter*
Incongruent	867 (93)	818 (94)
Congruent	768 (96)	728 (95)
Stroop effect	99 (3)	90 (1)

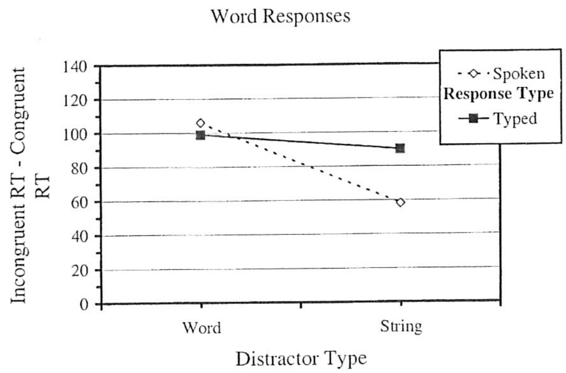

Fig. 31.5 Congruency effects as a function of distractor type and response type, comparing vocal and typed responses. Data are from the word-response conditions of Experiments 1 and 2.

crucial interaction between experiments, distractor type, and congruency is plotted in Fig. 31.5 in terms of congruency scores. The interaction approached significance, $F(1, 30) = 3.17$, $p < 0.09$, $MSE = 971.90$. Planned comparisons based on the error term from this three-way interaction showed that the two-way interaction between distractor type and congruency was significant for vocal responses, $F(1, 30) = 18.96$, $p < 0.01$, but not for typed responses, $F(1, 30) < 1.0$.

We analyzed the accuracy data in a 2 (distractor type) $\times$ 2 (congruency) ANOVA and found a significant main effect of congruency, $F(1, 15) = 8.39$, $p < 0.05$, $MSE = 3.30$. No other effects were significant.

31.6.1.3 Discussion

This experiment, with typewritten responses, showed no effect of distractor type on the magnitude of the Stroop effect. The Stroop effect was the same size whether the distractors were words or letters. We argue that letter distractors were as effective as word distractors because they activated the same initial response; the letter 'r' is typed the same way whether it is a single letter or the first letter in a word. The results contrast markedly with results with vocal responses from the whole-word response condition of Experiment 1, in which the Stroop effect was markedly smaller with letter distractors than with words.

The 95-ms Stroop effect observed here is smaller than the Stroop effects we reported in an earlier study of typewritten responses, which averaged 231 ms across four experiments (Logan and Zbrodoff, 1998). The difference is due to the composition of the trials. The present experiment consisted of 25% congruent trials, 75% incongruent trials, and 0% neutral trials, whereas the first three of our previous experiments consisted of 33% congruent, 33% incongruent, and 33% neutral trials. The Stroop effect is smaller when the proportion of congruent trials is smaller (Logan 1980; Logan and Zbrodoff 1979) and smaller when the proportion of neutral trials is smaller (Tzelgov, Henik, and Leiser 1990; Tzelgov, Henik, and Berger 1992), so it should be smaller in our present experiment than in our previous ones. In our fourth previous experiment, we manipulated the proportion of congruent and incongruent trials with no neutral trials. When 20% of the trials were congruent and 80% were incongruent, the Stroop effect was 123 ms, which is similar in magnitude to the present 95 ms effect.

31.7 General discussion

The two experiments converge on the conclusion that at least part of the Stroop effect is due to processes downstream from the dominant Stroop theories. The magnitude of the Stroop effect depends on the similarity between the responses evoked by the distractors and the responses required for the task. Word distractors evoke vocal responses that are very different phonetically and featurally from the vocal responses that letter distractors evoke, and so cause a stronger Stroop effect when the required response is a spoken word. Word distractors evoke typing responses that are similar to those evoked by letter distractors. Typed words consist of typed letters, and a letter is the same at the letter and movement level whether it is part of a word or a single object. Consequently, word and letter distractors cause Stroop effects of the same magnitude.

Our conclusion that the distractor type effect occurs downstream from the dominant Stroop theories depends on the contrast between Experiment 1 and Experiment 2. By themselves, the results of Experiment 1 can be explained by the dominant theories: word distractors are more likely to activate word responses than letter distractors, and so produce a stronger Stroop effect. However, the dominant theories cannot explain why typed words behave differently from spoken words. Downstream processes must be evoked to explain the difference.

Our conclusion suggests that Stroop theories should be broadened to include downstream processes as well as those that are part of the dominant theories. Stroop theorists have already broadened their theories to cover other phenomena in the attention literature. Logan (1980) addressed semantic priming as well as Stroop effects. Phaf *et al.* (1990) addressed selective attention as well as Stroop effects. Kornblum and colleagues addressed Stroop, Simon, and compatibility effects in a comprehensive framework and theory (Kornblum, Hasbroucq, and Osman 1990; Zhang *et al.* 1999). Our results suggest broadening in another direction, outside the attention literature, toward language production and motor control on the downstream end and reading and categorizing colors on the upstream end. Broadening in those directions would connect the Stroop and attention literatures to the larger literature on cognitive psychology and form the beginnings of a general theory of cognition (also see Logan 1995; Logan and Zbrodoff 1999).

Acknowledgments

This research was supported by Grant No. SBR 9808971 from the National Science Foundation. We are grateful to Julie Delheimer for testing the subjects and analyzing the data in these experiments and others in the series. We are grateful to Gary Dell for providing the phonetic transcriptions. We are grateful to Bernhard Hommel, Werner X. Schneider, Joseph Tzelgov, and an anonymous reviewer for helpful comments on the manuscript.

Note

1. Independently and jointly, Sylvan Kornblum and Gregory Stevens pointed out that the dimensional overlap model predicts Stroop-like interference from stimulus–stimulus congruence only when one or both of the stimulus properties is relevant to the response. Thus, the results of our unpublished experiment do not challenge the dimensional overlap model.

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