

Mapping symbols to response modalities: Interference effects on Stroop-like tasks

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Response compatibility effects were assessed with a Stroop-like task which involved arrow and word stimuli. The subjects were required to respond to one stimulus—an arrow (e.g., →) or a word (e.g., *left*)—and ignore the other. It was shown that response compatibility played a significant role in generating Stroop-like interference. Robust interference effects were observed when the subjects responded manually to word stimuli (ignoring irrelevant arrows) and when they responded vocally to arrow stimuli (ignoring irrelevant words). Smaller interference effects were observed under response-compatible conditions, namely, responding manually to arrows and vocally to words. In the second experiment, within-dimension displays (e.g., arrow–arrow or word–word displays) yielded a pattern of interference that did not interact with response modality. These findings indicate that both stimulus–response compatibility effects and target–distractor similarity are crucial for understanding Stroop-like interference.

Selective attention enables the processing of salient or relevant stimulus features, while suppressing other, irrelevant features. Numerous investigations have shown, however, that this selective process is not completely successful. For example, studies using Stroop-like tasks have demonstrated the interfering nature of irrelevant stimulus features on responses to target features (Dyer, 1973; Flowers, Warner, & Polansky, 1979; Keele, 1972; Lu & Proctor, 1995; MacLeod & Dunbar, 1988; McClain, 1983; Palef & Olson, 1975; Shor, 1970; Stroop, 1935; Treisman & Fearnley, 1969). These effects are typically reflected in slower response latencies in conditions in which the irrelevant feature is incongruent with the relevant target feature. For example, in the Stroop color-word task (Stroop, 1935), latencies to name the ink color of a stimulus are slowed when the stimulus itself is a color-word (e.g., the word *green* written in blue ink). *Stroop interference* is defined as the increase in reaction time (RT) in responding to incongruent stimulus arrays in comparison with congruent stimulus arrays or neutral arrays. A variety of Stroop and Stroop-like paradigms have provided useful information concerning attentional mechanisms (for a review, see MacLeod, 1991). Some of these paradigms include picture-word tasks (Smith & Magee, 1980), color-semantic associates tasks (Klein, 1964; Klopfer, 1996; Shaffer & LaBerge, 1979), cross-language tasks (Tzelgov,

Henik, & Leiser, 1990), and spatial location tasks (Clark & Brownell, 1975; Palef, 1978; Palef & Olson, 1975; Virzi & Egeth, 1985).

Several theories have been proposed to account for Stroop and Stroop-like interference (MacLeod, 1991). For example, theories based on automaticity or speed of processing suggest that the general facility or speed with which stimulus features are processed determines the magnitude of Stroop interference. Most relevant to the present study is the response-compatibility hypothesis, which states that interference is determined by the degree to which relevant and irrelevant features impinge on response-initiation processes. For example, in the original Stroop task, the irrelevant feature (a word) is more compatible with verbal responses than is the relevant feature (a color). As a result, color naming is affected by the presence of irrelevant words, but word naming is minimally affected by the presence of irrelevant colors. Several modifications of the Stroop task have clarified the importance of response compatibility (Beller, 1975; Fitts & Seeger, 1953; Flowers et al., 1979; Fox, 1992; Greenwald, 1972; Keele, 1972; Kornblum, Hasbroucq, & Osman, 1990; Lu & Proctor, 1995; Mascolo & Hirtle, 1990; McClain, 1983; Palef & Olson, 1975; Shimamura, 1987; Shor, 1970, 1971; Wang & Proctor, 1996). In these studies, manipulations of task variables, such as response modality (verbal vs. manual), affected the magnitude of Stroop interference.

A specific model of response compatibility, called the translational model, was developed by Virzi and Egeth (1985) to account for Stroop and Stroop-like interference. A modified version of their model is illustrated in Figure 1. To test their model, Virzi and Egeth used a spatial Stroop paradigm, in which words were presented in congruent locations on the screen (e.g., the word *right* located at the right side of the screen) or incongruent locations (e.g., the word *right* located at the left side of the screen).

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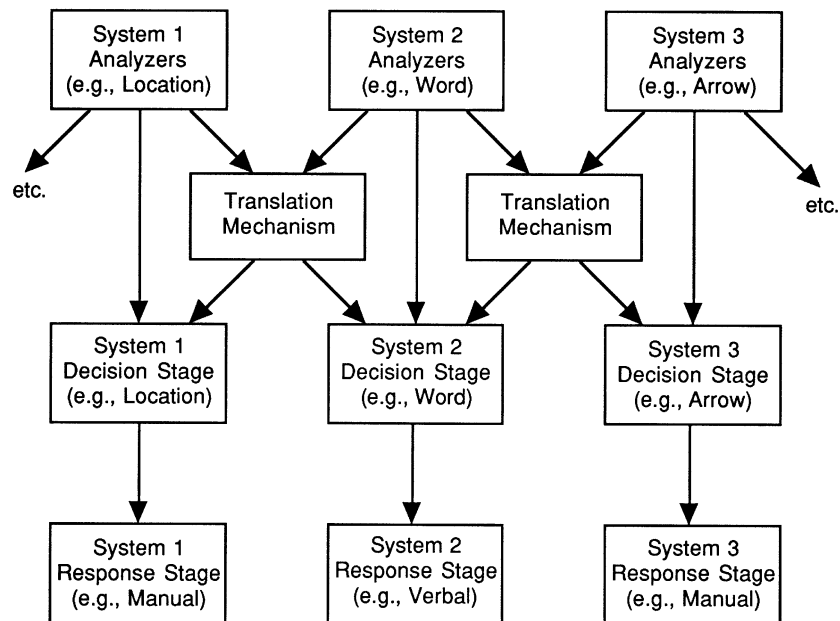


Figure 1. A modified version of the translational model of Virzi and Egeth (1985). Not shown are the translational links between System 1 and System 3. Other stimulus–response effects would require additional modular systems.

Their results showed that incongruent word stimuli did not interfere with manual responses to the spatial location of the stimuli. Likewise, incongruent spatial information did not impede vocal responses to word names. However, incongruent spatial information significantly slowed manual responses to word names, and incongruent word stimuli significantly slowed vocal responses to spatial locations.

In the translational model, separate modules are proposed for analyzing and responding to different stimulus features (e.g., words, colors, locations). On a given trial, if the stimulus and response are analyzed along the same processing path, no translation is required from the stimulus analyzer to the decision stage. This situation occurs, for example, when a verbal output is generated from a printed word stimulus. In such response-compatible situations, no interference is predicted, because responses are processed directly (without translation) and because the incongruent stimulus—for example, the spatial location—is processed by different path. However, when a vocal response must be made in order to identify the spatial location of an incongruent word stimulus, translation of the spatial information to a vocal decision stage is required. It is hypothesized that interference occurs because both the direct information (the incongruent word) and the translated information (the location) impinge on the same decision stage.

Some studies of response compatibility are consistent with the translational model (see, e.g., Mascolo & Hirtle, 1990; McClain, 1983), whereas others are not (see, e.g., O’Leary & Barber, 1993; Shor, 1971). O’Leary and Barber compared the spatial Stroop and response compatibility (Simon effect) paradigms in order to determine whether the Stroop and Simon effects were fundamentally related. They found that significant interference occurred, although

the translational model did not predict it. Specifically, interference effects were observed when participants responded vocally to word stimuli while ignoring location in the spatial Stroop paradigm. Indeed, even in Virzi and Egeth’s (1985) own experiments, there appeared a non-significant (8 msec) interference effect in a response-compatible condition, again when subjects responded vocally to a word while ignoring spatial location.

Another finding that was not predicted by the translational model was observed by Shor (1971). In this study, subjects responded to compound stimuli made up of a word written inside an arrow (e.g., the word *left* written inside a right-pointing arrow). Interference occurred when subjects identified the words with a manual response, but not when they made vocal responses to words (consistent with the model). However, comparable amounts of interference occurred when subjects responded manually and vocally to the arrow stimuli (not consistent with the model). It is possible that the use of symbolic (e.g., arrows and words) versus spatial (e.g., location) information may have generated this unpredicted pattern of data. For example, there is reason to believe that responding to the location of a stimulus with a manual response may involve specialized processes (for a review, see Lu & Proctor, 1995).

PRESENT STUDY

Whereas Virzi and Egeth (1985) distinguished between word and spatial location, we attempted to distinguish between two symbol types that can represent spatial directions, namely, words and arrows. Thus, we assessed the generality of the translational model using purely symbolic stimuli. In this way, we attempted to rule out overt

stimulus–response effects such as the Simon effect (Simon, 1990). That is, previous work has shown that manual responses have privileged access to spatially biased stimuli (Virzi & Egeth, 1985; Wang & Proctor, 1996). Although arrows and words are both symbols, there is some evidence to suggest that these stimuli are processed differently (Shimamura, 1987; Shor, 1970). In Experiment 1 of the present study, subjects responded to a word (i.e., *right* or *left*) or arrow target (i.e., \leftarrow or \rightarrow) while ignoring an irrelevant stimulus (a word or arrow). The important manipulation in this study was that of response modality. According to the translational model, large interference effects should be observed on incongruent trials when subjects make manual responses to word stimuli (ignoring arrows) and when they make vocal responses to arrow stimuli (ignoring words). That is, a distractor that is highly compatible with the response modality (i.e., words in the vocal condition and arrows in the manual condition) should produce a strong interference effect.

In contrast, according to the translational hypothesis, there should be no interference on the more compatible conditions (i.e., manual responses to arrows and vocal responses to words). However, on the basis of the results from previous studies (O’Leary & Barber, 1993; Virzi & Egeth, 1985), it was important to determine whether reduced but significant interference would be detected on these compatible conditions as well. Alternatively, on the basis of findings from Shor (1971), it was possible that the translational model would not aptly characterize findings from this arrow–word paradigm, inasmuch as spatial locations may be biased toward manual responding whereas arrows may not be.

Another factor manipulated in Experiment 1 of the present study was target–location predictability. In the Stroop color–word and Eriksen flanker tasks, target stimuli are presented in predictable locations (Eriksen & Eriksen, 1974). Yet, in Virzi and Egeth’s (1985) spatial Stroop paradigm, location predictability could not be manipulated, because location itself was an independent variable. The current paradigm, however, afforded the opportunity to compare directly conditions in which the target location was or was not predictable. It was hypothesized that target–location predictability would affect overall response times (RTs), but that it would not interact with response–compatibility effects.

In Experiment 2, we tested the effects of within- versus between-dimension displays. Between-dimension refers to the arrow–word displays used in Experiment 1 (see Figure 2a); within-dimension displays consisted of two stimuli from the same category—namely, two arrows (e.g., \rightarrow and \leftarrow) or two words (e.g., *right* and *left*; see Figure 2b). The translational model does not make specific predictions for within-dimension stimuli, but we expected that the pattern of response–compatibility effects would be different for within-dimension displays—that is, there would not be an effect of response modality. The presence of consistent within-dimension interference would implicate

mechanisms other than those outlined in the translational model.

Experiment 1

In the first experiment, the translational model described by Virzi and Egeth (1985) was tested. Instead of the spatial Stroop paradigm that was used by Virzi and Egeth, we used centrally presented displays that consisted of an arrow and a word. Also, this experiment explored the effect of target–location predictability by varying whether or not the target always appeared in the same location.

Method

Subjects. Thirty-six undergraduate students at the University of California, Berkeley, participated in the experiment as partial fulfillment of an undergraduate course requirement. All subjects reported being right-handed. There were 18 subjects in the predictable target condition and 18 subjects in the unpredictable target condition.

Design and Materials. Experiment 1 included three within-subjects variables—target stimulus (arrow vs. word), distractor congruency (congruent vs. incongruent), and response modality (manual vs. vocal). In addition, one between-subjects variable—predictability (predictable vs. unpredictable target location)—was manipulated across subjects. Block order was analyzed initially as a between-subjects variable, but it did not produce meaningful effects in preliminary analyses and thus was eliminated from further consideration. Similarly, the target being *right* or *left* (or \rightarrow vs. \leftarrow) did not have any effect, so all analyses are based on the scores averaged across left and right conditions.

When the target stimuli were arrows, the subjects were instructed to determine the direction indicated by them (left or right). When the target stimuli were words, subjects were instructed to respond to the direction indicated by the words (*left* or *right*). The congruency variable pertained to the direction indicated by a distractor stimulus, which could be congruent or incongruent with the direction indicated by the target stimulus (see Figure 2a). When arrows were targets, words were used as distractors, and when words were targets, arrows were used as distractors. In addition, neutral trials, in which the target stimulus appeared alone, were included. The response modality varied between blocks. For manual responses, subjects pressed one of two adjacent keys on a computer keyboard to indicate a left or right response. Subjects made responses using their index (respond left) and middle fingers (respond right) of their right hand. For vocal responses, subjects responded by speaking into a microphone, saying “right” or “left,” which activated a voice key.

Subjects were tested on four blocks of trials: (1) arrow targets, manual responses; (2) arrow targets, vocal responses; (3) word targets, manual responses; and (4) word targets, vocal responses. Each block consisted of 96 randomized trials: 32 congruent, 32 incongruent, and 32 neutral trials. The order of the four blocks was counterbalanced, so that there were six different possible block orders. Six subjects were run in each of these orders.

In the unpredictable target–location condition, the target appeared above central fixation on half of the trials and below fixation on the other half. That is, the target and distractor positions were randomly switched from trial to trial. In the predictable target–location condition, the target always appeared below the fixation point, and the distractor appeared above fixation. The subjects were not told explicitly of this configuration but had ample opportunity to discover it during practice.

The stimuli were presented on an IBM-PC compatible, using Micro Experimental Laboratory (MEL) software (Schneider, 1988). At the beginning of a trial, a fixation point (an asterisk), was presented centrally and subtended a visual angle of approximately 1°.

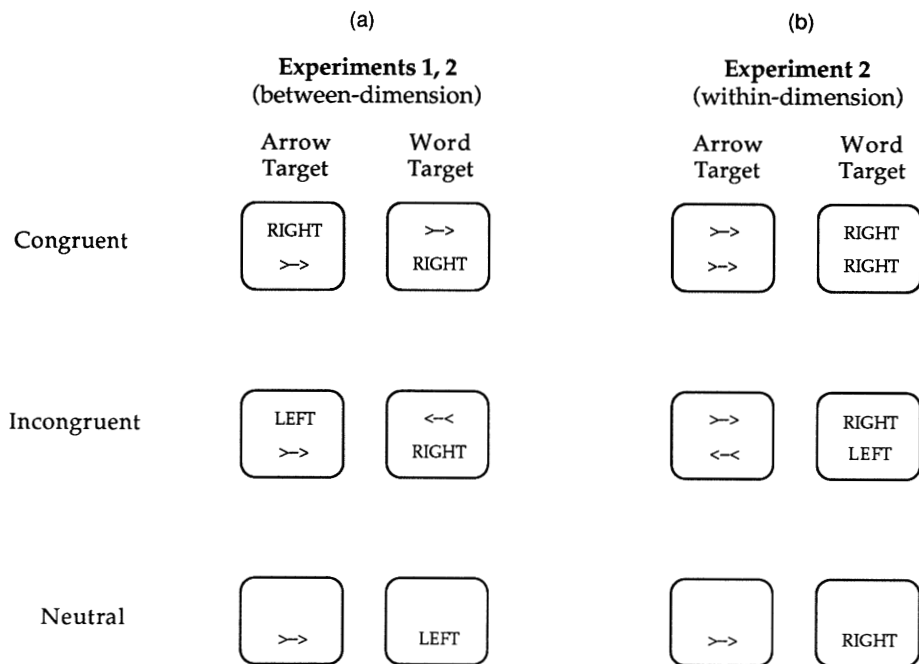


Figure 2. Examples of the stimulus displays for Experiments 1 and 2. These displays were presented centrally on the computer screen.

The target and distractor stimuli were white and appeared on the black background of the monitor. They were presented approximately 1° above or below the fixation point, and their length subtended a visual angle of approximately 5°.

Procedure. The subjects were tested individually and were seated approximately 70 cm from the computer monitor. Instructions were presented on the monitor and were also reiterated by the experimenter. The experimenter encouraged the subjects to respond quickly but without making errors. Before each block of trials, the subjects were given a set of 24 practice trials specific to that block condition. The experimenter monitored the practice blocks to ensure that the subjects were conforming to instructions.

At the beginning of each trial, the central fixation point was presented for 200 msec. The stimulus display was then presented and remained on until the subject made a response. For manual responses, the computer recorded the key pressed and the RT. For vocal responses, the voice key was used to measure the RT, and the experimenter recorded accuracy with a keypress. The intertrial interval was 2 sec. No feedback was given on incorrect trials, and incorrect trials were not rerun.

Results and Discussion

Error rates were very low and mirrored the RT data (i.e., there was no speed–accuracy tradeoff; see Table 1). Thus, errors were not subject to further statistical analysis. RTs from correct trials were analyzed in a $2 \times 2 \times 2 \times 2$ mixed analysis of variance (ANOVA) with target stimulus (arrow vs. word), distractor congruency (congruent vs. incongruent), and response modality (manual vs. vocal) as within-subjects variables and predictability (predictable vs. unpredictable target location) as a between-subjects variable. The criterion for significance in all of the analyses reported was set at $p < .05$. RTs from neutral trials were excluded from the ANOVA in order to simplify the inter-

pretation of any interactions. The mean RTs on neutral trials for the arrow target/manual, word target/manual, arrow target/vocal, and word target/vocal conditions were, respectively, 400, 473, 485, and 436 msec in the unpredictable target-location condition and 380, 431, 445, and 409 msec in the predictable target-location condition. Interference was characterized as the difference between congruent and incongruent RTs, which is consistent with Virzi and Egeth (1985). Mean interference in each condition is shown in Figure 3.

There was a main effect of distractor congruency—that is, the RTs on incongruent trials were slower than they were on congruent trials overall [$F(1,34) = 108.09, p < .001$]. There was a main effect of response modality, as manual RTs were generally faster than vocal RTs [$F(1,34) = 10.71, p < .01$]. Also, there was a main effect of predictability, such that the RTs were faster overall when the target location was predictable [$F(1,34) = 8.19, p < .01$]. However, predictability did not interact significantly with other factors. Because the predictability factor did not interact with any variables, the subsequent analyses were performed collapsed across this variable.

Importantly, the Stroop-like interference effect depended on other factors, as indicated by the significant interaction of target stimulus \times distractor congruency \times response modality [$F(1,34) = 41.42, p < .001$]. The significant three-way interaction indicates, as expected, that the amount of interference from arrow and word distractors depended on the response modality. Specifically, for manual responses, large interference effects were observed for word targets in the presence of arrow distractors. In contrast, for vocal responses, large interference ef-

Table 1
Response Times (in Milliseconds), With Standard Errors,
and % Error Rate as a Function of Condition for Experiment 1

Response	Arrow Target						Word Target					
	Congruent			Incongruent			Congruent			Incongruent		
	RT	$\pm SE$	%E	RT	$\pm SE$	%E	RT	$\pm SE$	%E	RT	$\pm SE$	%E
Unpredictable Target Location												
Manual	410	12	0.5	424	14	0.6	473	17	0.5	515	20	2.7
Vocal	483	14	0.3	533	15	1.1	443	13	0.1	453	15	0.3
Predictable Target Location												
Manual	380	6	0.3	382	9	0.5	419	8	0.7	459	14	0.9
Vocal	449	13	0.8	474	14	1.5	408	12	0.3	420	14	0.3

fects were observed for arrow targets in the presence of word distractors (see Figure 3). There was also a significant interaction of target stimulus \times response modality [$F(1,34) = 132.53, p < .001$], as manual responses to arrows were faster than were vocal responses to arrows, whereas vocal responses to words were faster than were manual responses to words.

In order to analyze further the response-compatibility effects, we performed interaction contrasts of target stimulus \times distractor congruency for the two different response modalities. This interaction contrast was significant in the manual condition [$F(1,35) = 28.55, p < .001$], as there was a much larger interference effect when subjects responded manually to words than when they responded manually to arrows. The interaction contrast was also significant in the vocal condition [$F(1,35) = 51.91, p < .001$], as there was a discrepancy in the congruent versus incongruent RTs for arrow targets, but little difference in the RTs for word targets. That is, in the vocal condition, there was more interference when subjects responded to arrows than when they responded to words, a pattern that is the opposite of the manual condition. Along with the overall three-way interaction, these contrasts verify that there was a crossover interaction in the data, such that the pattern of Stroop-like interference was reversed, depending on response modality.

Comparisons revealed that the RTs on incongruent trials were significantly slower than were those on congruent trials for the word target/manual condition [$F(1,35) = 44.42, p < .001$] and for the arrow target/vocal condition [$F(1,35) = 57.91, p < .001$], as was expected. However, there was also evidence of interference in the response-compatible conditions—that is, in the word target/vocal condition [$F(1,35) = 15.35, p < .001$] and in the arrow target/manual condition [$F(1,35) = 3.87, p = .06$].

Summary

The results from this experiment supported the hypothesis that Stroop-like interference effects are generated by both arrow and word distractors, but that the amount of interference depends on the response modality. Specifically, the RTs in manual conditions were particularly slowed by arrow distractors. Conversely, the RTs in vocal conditions were particularly slowed by word distractors. These findings suggest a compatibility effect for arrows in manual

responses and a similar effect for words in vocal responses. Such results are consistent with the translational model. However, comparisons of congruent versus incongruent RTs reflected small but significant interference effects when no translation process was required—for example, in the word target/vocal condition. According to the translational model, there should be no effect of the distractors in this condition. This issue will be discussed further in the General Discussion.

The other important finding in Experiment 1 was that the predictability of target location did not affect the pattern of data, although it reduced the magnitude of the RTs. Even when the subjects could focus attention on a particular location, there were robust response-compatibility effects.

Experiments 2A and 2B

In the second experiment, we assessed the pattern of interference effects when targets and distractors were represented by the same symbol type. That is, we were interested in the pattern of RTs to stimulus displays consisting of two incompatible arrows (\rightarrow and \leftarrow) or two incompatible words (*right* and *left*). We refer to such displays as within-dimension displays and distinguish them from those used in Experiment 1, which we refer to as between-dimension displays (see Figure 2). Such a distinction between within- and between-dimension displays has been studied recently by Cohen and Shoup (1997). In Experiment 2A, all subjects responded manually, and in Experiment 2B, all subjects responded vocally.

The translational model as described above does not make any predictions about the outcome of such within-dimension displays. However, we infer that the model would predict that the two stimuli in within-dimension displays are processed by the same analyzers—for example, the two arrows in a double arrow display are processed by the same arrow/directionality module. This means that competition at the decision stage can arise from two different situations—from two stimuli that arrive from the compatible analysis module (e.g., the words *left* and *right* in the vocal condition) or from two stimuli that have been translated (e.g., the words *left* and *right* in the manual response condition). Contrary to Experiment 1, it was predicted that there would *not* be an interaction of distractor congruency, response modality, and target stimulus. That is, for within-dimension stimulus displays, both stimuli

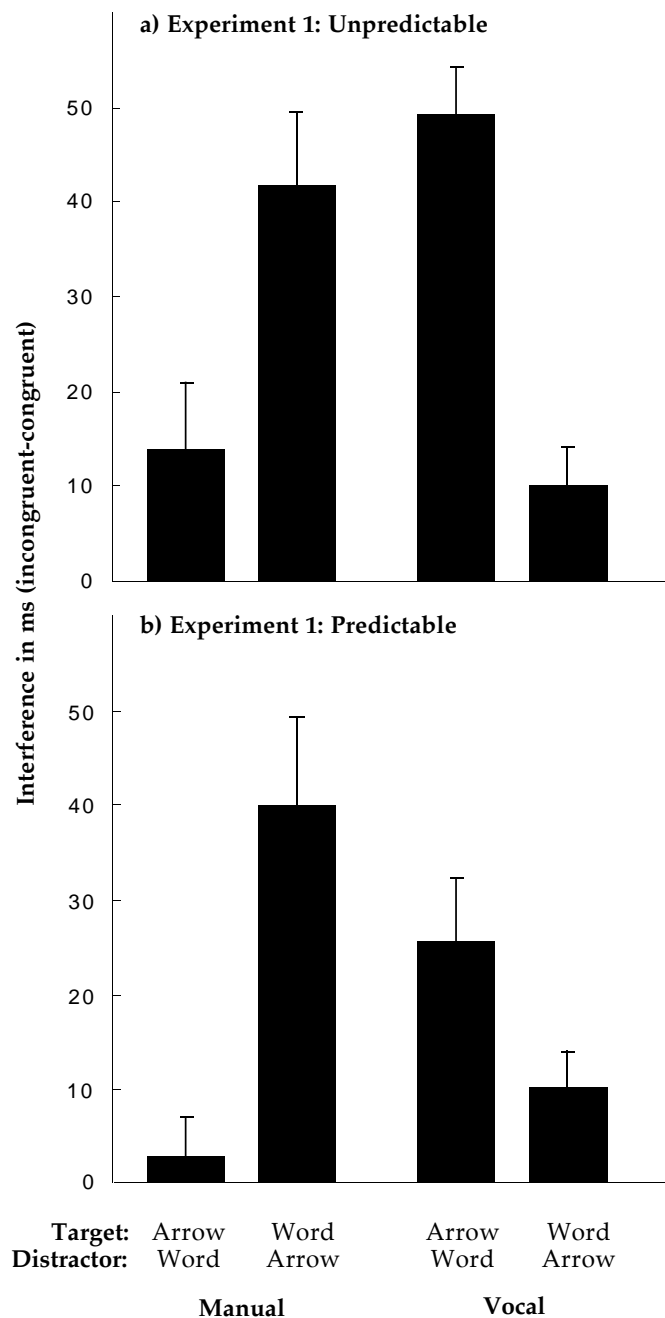


Figure 3. Interference (incongruent minus congruent reaction times) as a function of response modality—manual or vocal—and target stimulus—arrow or word—for the predictable and unpredictable target location conditions of Experiment 1. Error bars shown represent one standard error, calculated separately for each condition mean.

should always arrive at the same decision stage at approximately the same time, regardless of response modality, and, thus, there should be comparable amounts of interference.

Method

Subjects. Forty-eight students at the University of California, Berkeley, participated in Experiment 2 as partial fulfillment of an undergraduate psychology course. These subjects had not taken part

in any previous, related experiments. The 24 subjects in the manual-response condition (Experiment 2A) were required to be right-handed. There was no handedness requirement for the 24 subjects in the vocal-response condition (Experiment 2B). All subjects signed informed-consent forms prior to the experiment.

Design and Materials. Experiments 2A and 2B included three within-subjects variables—target stimulus (arrow vs. word), distractor congruency (congruent vs. incongruent), and dimension similarity (within-dimension vs. between-dimension). Because this ex-

Table 2
Response Times (in Milliseconds), With Standard Errors,
and % Error Rate as a Function of Condition for Experiment 2

Condition	Arrow Target						Word Target					
	Congruent			Incongruent			Congruent			Incongruent		
	RT	±SE	%E	RT	±SE	%E	RT	±SE	%E	RT	±SE	%E
Experiment 2A: Manual Response												
Within-dimension	414	11	0.1	433	11	0.3	480	14	0.4	490	15	1.0
Between-dimension	413	11	0.4	419	11	0.8	446	10	0.3	487	12	0.3
Experiment 2B: Vocal Response												
Within-dimension	486	11	0.2	496	12	0.0	439	10	0.2	446	11	0.2
Between-dimension	485	14	0.1	519	16	0.3	428	10	0.2	428	10	0.4

Note—Within-dimension refers to arrow–arrow and word–word displays; between-dimension refers to arrow–word displays.

periment involved the addition of another within-subjects variable (dimension similarity), time limitations prevented the assessment of the response-modality variable as a within-subjects manipulation. Instead, we performed two experiments that were identical except for response modality. The subjects in Experiment 2A made manual responses, whereas subjects in Experiment 2B made vocal responses. Thus, response modality was assessed as a between-subjects factor in Experiment 2.

The variable of target–distractor similarity (within- and between-dimension conditions) was manipulated across blocks of trials. On blocks in which between-dimension stimuli were used, the displays were identical to those used in the predictable target-location condition of Experiment 1 (see Figure 2a). On blocks in which within-dimension stimuli were used, the stimulus displays consisted of either two arrows or two words (or on neutral trials, only one stimulus; see Figure 2b).

The subjects identified the direction represented by a stimulus (arrow or word) that appeared below a central fixation point. They were instructed to ignore any stimulus that occurred above the fixation point. Thus, as in the predictable-location target condition of Experiment 1, the target stimulus always appeared in the same location. Also, as in the previous experiment, the target stimulus was blocked, such that in each block the target stimuli were either words or arrows. Subjects were tested on four blocks of trials: (1) arrow targets, between-dimension; (2) arrow targets, within-dimension; (3) word targets, between-dimension; and (4) word targets, within-dimension. There were six different block orders, and 8 subjects were run in each of these. All other details were identical to those in Experiment 1.

Procedure. The procedure was identical to that in Experiment 1, except that the subjects were explicitly told to respond only to the stimulus appearing below fixation.

Results and Discussion

As in Experiment 1, error rates were very low and reflected the pattern of the RTs (see Table 2). Again, there was no evidence of a speed–accuracy tradeoff, and thus errors were not subject to further analysis. The RTs from correct trials were analyzed in a 2 × 2 × 2 × 2 mixed ANOVA with target stimulus (arrow vs. word), distractor congruency (congruent vs. incongruent), and dimension similarity (within-dimension vs. between-dimension) as within-subjects variables and response modality (manual vs. vocal) as a between-subjects variable. Data are shown in Table 2. The RTs from neutral trials were not included in the overall ANOVA. The mean RTs on neutral trials for the arrow target/within-dimension, word target/within-dimension, arrow target/between-dimension, and word

target/between-dimension were, respectively, 403, 477, 412, and 473 msec in Experiment 2A and 479, 432, 490, and 422 msec in Experiment 2B. Mean interference in the four conditions of Experiments 2A and 2B are shown in Figure 4.

There was a main effect of distractor congruency [$F(1,46) = 77.02, p < .001$], as the RTs on congruent trials were faster than those on incongruent trials overall. No other main effects were significant, but there were several significant interactions. There was a significant interaction of target stimulus × dimension similarity [$F(1,46) = 6.98, p < .05$]. This reflected the fact that the RTs for arrow targets were comparable across within- and between-dimension conditions, whereas the RTs for word targets were shorter overall in the between-dimension conditions than in the within-dimension conditions. There was also an interaction of distractor congruency × dimension similarity [$F(1,46) = 9.73, p < .01$], as overall interference was greater in the between-dimension than in the within-dimension conditions.

There were several significant interactions with response modality. There was a significant interaction of target stimulus × response modality [$F(1,46) = 74.78, p < .001$], as manual RTs were generally faster for arrow targets than for word targets, whereas vocal RTs were faster for word targets than for arrow targets. There was an interaction of target stimulus × distractor congruency × response modality [$F(1,46) = 18.16, p < .001$]. This interaction reflects the fact that there was more interference from arrow distractors in manual response conditions but more interference from word distractors in vocal response conditions. Last, there was an interaction of target stimulus × distractor congruency × dimension similarity × response modality [$F(1,46) = 44.07, p < .001$]. As was predicted, the significant four-way interaction results from the fact that the pattern of interference in the between-dimension conditions was reversed when manual and vocal responses were compared (i.e., there was more interference when responding manually to words but more interference when responding vocally to arrows), but there was no such reversal in the pattern of interference in the within-dimension conditions when manual and vocal re-

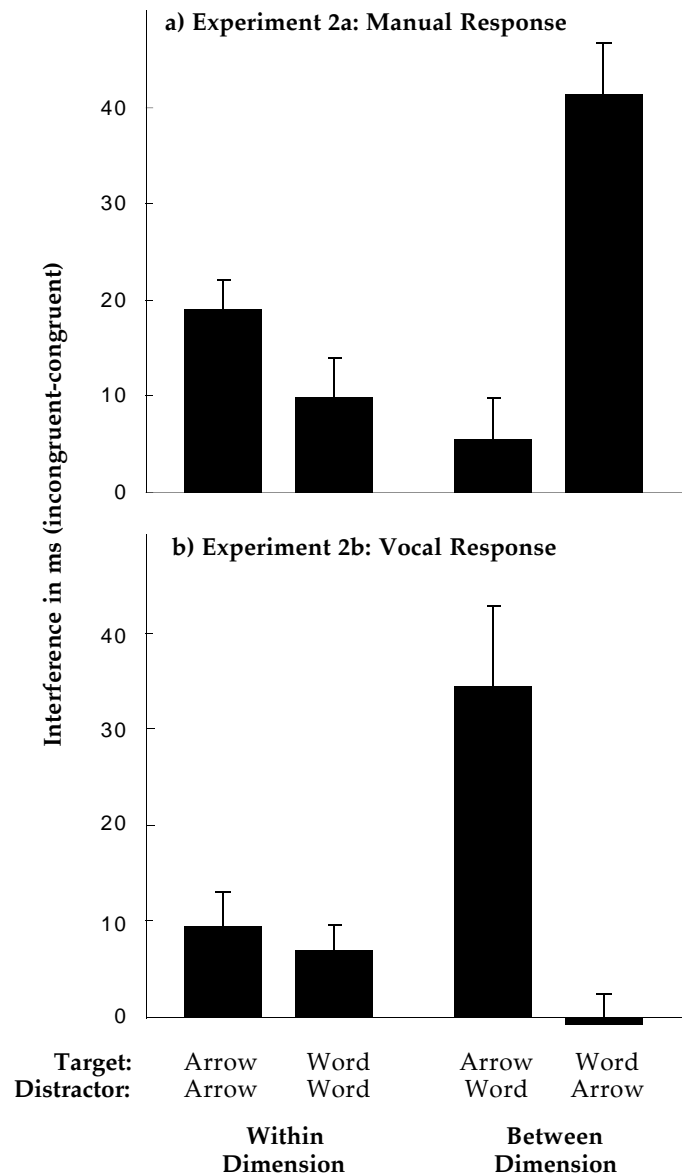


Figure 4. Interference (incongruent minus congruent reaction times) as a function of the dimension condition—within- or between-dimension—and target stimulus—arrow or word—for Experiments 2A (manual response) and 2B (vocal response). Within-dimension refers to arrow–arrow and word–word displays; between-dimension refers to arrow–word displays. Error bars shown represent one standard error, calculated separately for each condition mean.

sponses were compared. That is, in the within-dimension conditions, there was more comparable interference from arrow and word distractors, regardless of response modality. However, in Experiment 2A (see Figure 4a), there was a discrepancy in the degree of interference on the arrow target/within-dimension condition (19 msec) in comparison with the word target/within-dimension condition (10 msec). This difference was not predicted, and thus a post hoc comparison of these two conditions was conducted to determine the significance of this effect. This difference was

not significant ($p > .20$). It is still possible that this non-significant difference may be reflecting an important difference in processing arrows versus words in the manual domain, but the individual subjects' data were possibly too variable to detect such a difference.

We performed post hoc interaction contrasts to assess performance when the subjects responded only to the non-translated target stimulus (arrows in Experiment 2A and words in Experiment 2B). In Experiment 2A, the interaction contrast compared the congruency effect between

arrow target/within-dimension and arrow target/between-dimension conditions. This analysis revealed a significant dimension similarity \times distractor congruency interaction [$F(1,23) = 5.58, p < .05$; see Figure 4a]. This interaction reflects the fact that interference was greater from arrow distractors than from word distractors when subjects responded to arrow targets. Most likely, this is because, when the subjects responded to arrows with word distractors, the arrow stimuli were processed quickly and directly through the compatible, manual response stream. When the subjects responded to arrows with arrow distractors, both stimuli in the display were processed by the same analysis module, and thus there was competition at the decision stage.

In Experiment 2B, the post hoc interaction contrast compared the congruency effect between word target/within-dimension and word target/between-dimension conditions and revealed a trend for a dimension similarity \times distractor congruency interaction [$F(1,23) = 3.11, p = .09$; see Figure 4b]. That is, there was a trend for greater interference from word distractors than from arrow distractors when subjects were responding to words. Again, this is probably due to the fact that, in the within-dimension condition, two words arrive and compete at the same decision stage, whereas in the between-dimension condition, the irrelevant arrow is processed by an irrelevant (i.e., nonvocal) analysis module. This trend complements the significant interaction observed for arrow targets with manual responses in Experiment 2A.

In Experiment 2A, the RTs on the incongruent trials were longer than those on the congruent trials for the arrow target/within-dimension condition [$F(1,23) = 35.88, p < .05$], the word target/within-dimension condition [$F(1,23) = 5.43, p < .05$], and the word target/between-dimension condition [$F(1,23) = 57.91, p < .05$]. There was no significant interference on the arrow target/between-dimension condition [$F(1,23) = 1.59, p = .22$]. In Experiment 2B, the RTs on the incongruent trials were longer than those on the congruent trials for the arrow target/within-dimension condition [$F(1,23) = 7.02, p < .05$], the word target/within-dimension condition [$F(1,23) = 5.57, p < .05$], and the arrow target/between-dimension condition [$F(1,23) = 17.98, p < .05$]. There was no interference on the word target/between-dimension condition [$F(1,23) = .08, p = .93$].

Summary

In Experiment 2, the between-dimension conditions were the same as those in Experiment 1, and the same pattern of results was observed. Specifically, there were disproportionately large congruency effects when subjects responded manually to word targets with arrow distractors and when they responded vocally to arrow targets with word distractors. These data are consistent with the translational model of Stroop interference. Data from the within-dimension conditions showed a different pattern, one not predicted by the translational model. Both arrow and word

target conditions produced comparable interference effects, regardless of response modality. That is, responding to arrow targets with arrow distractors produced the same amount of interference, regardless of response modality; similarly, responding to word targets with word distractors produced comparable amounts of interference in both manual- and vocal-response conditions.

GENERAL DISCUSSION

The present investigation demonstrated response-compatibility effects in an arrow–word Stroop-like paradigm. That is, arrow stimuli were compatible with manual responses, and word stimuli were compatible with vocal responses. Indeed, incongruent arrows produced robust interference when the subjects made manual responses to words, but incongruent words had less effect when the subjects made manual responses to arrows. Similarly, incongruent words produced robust interference when the subjects made vocal responses to arrows, but incongruent arrows had less effect when they made vocal responses to words. Moreover, the findings were replicated even under relatively low attentional demands—that is, when target location was predictable and consistent. Last, we showed that within-dimension displays (e.g., arrow–arrow or word–word displays) produced a different pattern of interference, such that Stroop-like interference did not depend on response modality. That is, incongruent arrows slowed responding to target arrows in both manual and vocal conditions, and incongruent words slowed responding to target words in both manual and vocal conditions. These results extend those of previous studies that used similar stimuli (Beller, 1975; Shimamura, 1987; Shor, 1970, 1971).

To some extent, our data depart from the translational model proposed by Virzi and Egeth (1985), inasmuch as we detected some interference when subjects responded vocally to word stimuli and manually to arrow stimuli. Such interference effects were not predicted by the translational model, because the incompatible, irrelevant distractor should not have interfered with the more direct, compatible target. According to the translational model, only the target stimulus is translated, when necessary; the irrelevant dimension is not obligatorily translated.

One possible explanation for these unpredicted effects is that our task was more sensitive in detecting interference than other studies were. In the present study, we included neutral trials. Previous studies with Stroop-like tasks have shown that interference on incongruent trials can be enhanced by including a larger proportion of congruent trials (MacLeod, 1991). Perhaps the neutral trials (in which the target was presented alone) acted like congruent trials and enhanced Stroop interference in our experiments. Also, another study reported interference effects although the translational model did not predict them—for example, when subjects responded vocally to word stimuli while ignoring location in a spatial Stroop paradigm (O’Leary & Barber, 1993).

Our findings are not completely consistent with a previous study using a similar arrow–word paradigm (Shor, 1971). In that study, manual and vocal responses to arrows with word distractors resulted in comparable amounts of interference. One explanation is that the arrow stimuli that were used in that study were rather unusual, involving large rectangles with a point on one end. These stimuli may not have been very compelling as indicators of direction. Second, the reported data that compared manual with vocal conditions were collected using four-direction stimulus sets (i.e., up, down, left, and right). It may be that the right–left distinction is more salient than is the up–down distinction (Shor, 1970), and, thus, that the inclusion of the latter diluted the results.

The results from the present experiments can be related to the translational model proposed by Virzi and Egeth (1985). That is, the magnitude of Stroop interference effects is predicted by the amount of interference that is caused by irrelevant information at a specific response stage. The model argues against a simple speed-of-processing model of Stroop interference, in which two inputs compete at a single response stage. Rather, the translational model proposes that there are two (or more) separate input–output processing streams—for example, one for spatial information/manual responses and one for lexical information/vocal responses. It is possible for one of these input modules to lead directly to a decision-and-response stage, if the information does not need to be translated. This occurs, for example, when a vocal output is generated from a word stimulus or when a manual output is generated from location information. Such response-compatible processes occur directly, and, thus, there is no interference from an incongruent stimulus. Translation occurs, however, when a word stimulus requires a manual response or when location information requires a vocal response. Interference arises because the more compatible, though irrelevant, response will be activated in addition to the relevant response. Thus, irrelevant word information interferes significantly with vocal responses made to spatial information, whereas irrelevant spatial information interferes significantly with manual responses to word information.

Despite the success of the translational model, it has several problems. Virzi and Egeth (1985) point out that, as the number of Stroop-like asymmetries increases, the model becomes unparsimonious. That is, separate modules that include input, translation, decision, and output stages are required for every Stroop-like interference effect. For example, we would have to add an arrow/directional module to Figure 1 just to handle the present results. A second problem with the translational model is that it does not predict interference when subjects respond vocally to words or manually to arrows. Finally, it makes no predictions for the within-dimension interference observed in Experiment 2, which does not depend on response modality.

Rather than proposing separate modules, with translation an all-or-none process, we propose that translation is always required. Translation may be relatively easy (e.g., responding verbally to a printed word) or difficult (e.g.,

responding verbally to an arrow). Thus, the subject can be viewed as gathering evidence relevant to the task. This evidence must always be translated into a response decision, and it is the difficulty of this translation that causes the asymmetry in Stroop-like tasks.

The ease of translating aspects of stimulus information can readily explain our results. The interference effects on the within-dimension conditions were smaller in magnitude than those observed in between-dimension conditions in which the target feature was incompatible with the response modality. Yet, these within-dimension effects were larger than those observed in between-dimension conditions in which the target feature was compatible with the response modality. These findings are consistent with a model that suggests that the magnitude of interference is determined by the degree to which irrelevant information has been processed by a response-decision stage. Thus, it is difficult to attend to arrows and ignore irrelevant words when vocal responses are required, because the irrelevant lexical information is presumed to impinge on a vocal decision stage *prior* to the arrival of the target feature. For within-dimension conditions, both the target and irrelevant features impinge on a response-decision stage nearly simultaneously, regardless of the response modality. Finally, for between-dimension conditions in which the irrelevant feature is less compatible, the effect of this feature is minimal, because processing that stimulus occurs *after* processing proceeds for the target stimulus. Thus, an explanation of Stroop-like interference that invokes both speed-of-processing and response-compatibility principles may aptly characterize the present findings.

An alternative interpretation of within-dimension interference effects is that this kind of interference occurs at a processing stage that precedes response decisions. Recently, Cohen and Shoup (1997) studied within- and between-dimension effects, using a flanker task. In their study, the two dimensions were color and line orientation. They found that when the flanker was from a different dimension than the target (e.g., a red target with a diagonal line distractor), the irrelevant flanker did not cause interference, even though it was mapped to a different key response, whereas a within-dimension display (e.g., a red target with a blue distractor) did cause interference. They interpreted these data in the following way: Interference from within-dimension stimuli occurs at a response-*selection* stage (particular to that dimension), which precedes the response-*output* stage. For between-dimension displays, the two stimuli are processed by separate response-selection stages (one for color and one for orientation), and thus no interference occurs.

Our results do not agree completely with Cohen and Shoup's (1997) findings. For example, we detected significant interference effects when stimuli were processed by separate response-selection stages (i.e., for arrows and for words). An important difference between our stimuli and those of Cohen and Shoup is that, in their experiments, dimensionality was determined by basic features, such as color and orientation, whereas, in our study, it was deter-

mined by different symbol types. This may account for the discrepancy, inasmuch as color and orientation may be analyzed by more separable processing streams.

In summary, the results from the experiments reported here confirmed the importance of stimulus–response compatibility effects on Stroop-like interference. Specifically, when subjects made responses to arrow–word displays, the magnitude of interference was determined by the interaction of response modality and target stimulus. We broadened previous results by showing that such compatibility effects can be observed using purely symbolic stimuli and that these effects remain even when attentional demands are reduced. In the last experiment, when the subjects made responses to arrow–arrow or word–word displays, the magnitude of interference was less dependent on the relationship between the stimulus and the response, which suggests that the relationship of the two stimulus features (target and distractor) also plays an important role.

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