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Attention and Automaticity in Stroop and Priming Tasks: Theory and Data

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Three major variables identified with attention and automaticity in the priming paradigm are shown to have parallel effects in the Stroop paradigm. A model is developed to explain the effects in both paradigms in terms of a single decision process that combines evidence from several sources (e.g., habitual associations and temporary contingencies between the prime and the target or between the unreported and reported dimensions). The model is applied to two Stroop experiments in which the faster two of three stimulus dimensions relate associatively and cue through a frequency manipulation the third, which must be reported. Depending on the direction of the cueing relation, attentional effects enhanced or counteracted automatic (associative) effects, and the attentional effects were stronger with the faster unreported dimension than with the slower one. These results corroborate findings in the priming paradigm and confirm the model. Implications of the results and the model for broader issues are discussed.

INTRODUCTION

The distinction between automatic and attentionally-controlled modes of processing has long been considered important in understanding the mechanics of thought (e.g., Bryan & Harter, 1899). Over the years, substantial effort has been invested in developing methods to determine whether a process is automatic or attentionally controlled (LaBerge, 1973; Logan, 1979; Posner & Snyder, 1975a) and in specifying conditions under which an attentionally-controlled process will become automatic (Logan, 1979; Shiffrin & Schneider, 1977; Solomons, 1899; Spelke, Hirst, & Neisser, 1976). These studies have focused primarily on "pure" cases of attention and automaticity, and have relatively little to say about tasks that require a coordinated mixture of both modes of processing. Since many interesting tasks seem to be of this type (e.g., reading, LaBerge & Samuels, 1974; typewriting, Sternberg, Monsell, Knoll, & Wright, 1978; and arithmetic, Hitch, 1978), the problem of coordinating modes of processing is important in itself. Recently, studies in the priming paradigm have begun to produce a body of theory and data on the interaction

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between automatic and attentionally-controlled modes of processing which promises to generalize to a wide variety of situations (e.g., LaBerge, Petersen, & Norden, 1977; Neely, 1976, 1977; Posner, 1978; Posner & Snyder, 1975a,b). The purpose of this article is to extend the theory and the empirical principles to the Stroop paradigm. First, it is shown from published data that the major variables affecting the interaction between attention and automaticity in the priming paradigm have parallel effects in the Stroop paradigm. Then, the two paradigms are expressed as special cases of a general model, which accounts for the effects of the major variables in terms of a composite decision process that combines evidence from several sources. Finally, two experiments are reported which strengthen the empirical parallels drawn from existing data and allow a test of the model's ability to handle the major variables in the Stroop paradigm.

Parallel Effects in Priming and Stroop Tasks

The priming paradigm requires a judgment about a target stimulus, which is preceded by a priming stimulus, related to the target in some way. For example, the target may be a letter string which the subject must classify as a word or nonword, and the prime may be a word associated with the target. Although the response depends primarily on information from the target, relations between the prime and the target have subtle influences on performance. Accuracy is generally high so the effects are seen in reaction time; performance is facilitated when the relations are consistent with what the subject "expects," and inhibited when they are not. The paradigm represents real-world situations in which one object (or event) cues another, independent object (or event). For example, function words can cue the grammatical constituents of a sentence (Clark & Clark, 1977); also bodily movements can cue the emotional interpretation of a speaker's utterance (Mehrabian, 1969).

The Stroop paradigm requires a judgment about one dimension of a multidimensional stimulus in which other dimensions may conflict with or agree with the judged dimension. For example, the judged dimension may be color, which the subject must name aloud, and the unjudged dimension may be form, which specifies a word representing a compatible or conflicting color. Again, the response depends primarily on the judged dimension, but performance is influenced subtly by relations between judged and unjudged dimensions. Performance is facilitated when relations are consistent with expectation and inhibited when they are not. The Stroop paradigm represents real-world situations in which one property of an object (or event) cues another property of the same object (or event). For example, the length and shape of a word can cue its identity (Rayner, McConkie, & Ehrlich, 1978), and the intonation of a word can cue its interpretation (Clark & Clark, 1977).

In both paradigms, only one source of information need be attended to respond appropriately (i.e., the target stimulus or the judged dimension), yet subjects are influenced by other sources (i.e., the prime or the unjudged dimensions). The major difference is that the different sources represent different stimuli in the priming paradigm and different dimensions of one stimulus in the Stroop paradigm. This difference may not be critical, depending in general on how the term "stimulus" is defined and in particular on how the stimulus is represented in the theory describing the underlying processes (e.g., see Kahneman & Henik, 1979). More important is the point that both paradigms provide (at least) two sources of information, and that performance is influenced by the relation between them. The form of the influence is determined largely by three major variables: (1) the nature and strength of prior associations between the two sources, (2) the nature and strength of current predictive relations between the two sources, and (3) the time elapsing between the availability of information from each source. Each of these variables has parallel effects in the two paradigms.

Prior associations. In both paradigms, the influence of familiar relations or prior associations between the two sources of information is usually attributed to automatic processing. The relations or associations are acquired through long experience with the materials, under conditions believed necessary and sufficient for the development of automaticity (i.e., consistent mapping; see Logan, 1979; Shiffrin & Schneider, 1977). Moreover, they seem to have the same influence regardless of the direction of attention, independent of the subject's intention (see Posner & Snyder, 1975a), which suggests they are processed in a strategy-invariant manner.

Prior associations between "relevant" and "irrelevant" sources of information have usually facilitated performance in the priming paradigm (see Posner, 1978, for a review) and inhibited performance in the Stroop paradigm (for reviews, see Dyer, 1973; Jensen & Rohwer, 1966). Most likely, this reflects differences in typical procedure rather than fundamental differences between the paradigms. Priming studies usually use primes that relate positively to the target, for example, the target may be a common associate of the prime or a member of the category named by the prime. By contrast, Stroop studies usually use unreported dimensions that relate negatively to the target dimension, for example, an unreported dimension may specify a value opposite to or otherwise different from the value of the reported dimension. Indeed, priming stimuli that relate negatively to the target, such as atypical associates, can produce inhibition

(Neely, 1977; Rosch, 1975), and unreported dimensions that relate positively to the reported dimension can produce facilitation (Palef, 1978). In both paradigms, facilitation and inhibition effects are larger the stronger the association between relevant and irrelevant information (e.g., Fox, Shor, & Steinman, 1971; Warren, 1974, 1977).

Novel relations. Attentional effects are usually studied by introducing novel cueing relations between relevant and irrelevant sources of information so that one source signals or predicts the other. The novelty of the relations rules out automatic processing, and the rapid adjustment to changes in the relations suggests the strategic flexibility characteristic of attentional processing (Logan, 1979; Posner & Snyder, 1975a).

The major variable for investigating attentional effects is the validity of the cueing relation, defined operationally as the conditional probability of some aspect of the target stimulus or reported dimension given the priming stimulus or unreported dimension. Posner and Snyder (1975b) have shown convincingly that in the priming paradigm the amount of facilitation and inhibition observed increases with cue validity (also see Tweedy, Lapinski, & Schvaneveldt, 1977). Recently, Logan and Zbrodoff (1979) varied the relative frequency of compatible and conflicting trials in the Stroop paradigm to make the unreported dimension a more-or-less valid cue to the reported dimension, and found that facilitation and inhibition increased with cue validity, as in the priming paradigm.

The most convincing demonstration of attentional effects occurs when cue validity is pitted against prior associations to reverse their effects. Neely (1977) provided a clear example in the priming paradigm using a lexical decision task. In his procedure, the priming stimulus BODY was more likely to be followed by a target word that referred to a part of a building (e.g., DOOR) than by a target word that referred to a part of a body (e.g., ARM). Given time to attend to the prime, subjects were considerably faster in the former case, which confirmed expectation but opposed prior associations, than they were in the latter, which confirmed prior associations but opposed expectation. Logan and Zbrodoff (1979) demonstrated similar effects in the Stroop paradigm: Their subjects reported a word (ABOVE or BELOW) that appeared above or below a fixation point. When conflicting trials (e.g., ABOVE/below and BELOW/above) were more frequent than compatible trials (e.g., ABOVE/above and BELOW/below) so that the identity of the word was likely to be the opposite of its position (contrary to prior association), subjects were considerably faster responding to conflicting stimuli than to compatible ones, reversing the usual Stroop effect.

Timing effects. The time at which information from relevant and irrelevant sources becomes available is important because it limits the opportunity for one source to influence and be influenced by the other, and so determines the "blend" of automatic and attentional effects. In the priming paradigm, the time-course of opportunity for influence is manipulated by varying the delay between the onset of the priming stimulus and the onset of the target. Most studies show that the delay must be greater than 200–500 msec for facilitation and inhibition to have their strongest effects (e.g., Neely, 1976, 1977; Posner & Snyder, 1975b; Rosch, 1975; Thomas, 1974; Warren, 1977). There is some evidence that attentional facilitation and inhibition take longer to reach their maxima than automatic and associative facilitation and inhibition, possibly reflecting the time required to attend to the prime (see Posner, 1978).

In the Stroop paradigm, opportunity for influence is manipulated by choosing reported and unreported dimensions that become available at different times. Palef and Olson (1975) have derived an "empirical rule" for Stroop effects which states that facilitation and inhibition can occur only when an unreported dimension is available before a decision is made about the reported dimension. They provided evidence that automatic effects follow this rule (also see Clark & Brownell, 1975; Murray, Mastronadi, & Duncan, 1972; Palef, 1978), and there is some evidence that attentional effects may follow it as well: Logan and Zbrodoff (1979) introduced a valid cueing relation between two stimulus dimensions and found facilitation and inhibition only when the slower dimension was reported.

To summarize, there is evidence that the amount of facilitation and inhibition observed in both the priming paradigm and the Stroop paradigm depends on the nature and the strength of prior associations between relevant and irrelevant sources of information, on the nature and the strength of current predictive relations between them, and on temporal factors which determine the opportunity for mutual influence, supporting the contention that attention and automaticity have parallel effects in the two paradigms. The evidence on attentional effects and their interaction with temporal factors is weaker in the Stroop paradigm, however, and the experiments reported here were designed, in part, to remedy that weakness.

Facilitation, Inhibition, and Combining Evidence

The patterns of facilitation and inhibition observed in the two paradigms can be explained by a single mechanism that combines evidence from different sources and selects a response on the basis of the combined information. Well-established associations and temporary predictive relations between the prime and the target or the unreported and the reported dimensions may act as sources of evidence in making the required decision. When the stimulus configuration is compatible with habitual associations or with current predictions (or with both), the evidence they provide reduces the evidence required from the target or reported dimension to choose a response with an acceptable level of accuracy; when the stimulus configuration conflicts with associations or predictions (or both), the evidence they provide is misleading and increases the evidence required from the target or reported dimension. On the common assumption that evidence accumulates over time, compatible configurations should reduce or facilitate reaction time and conflicting configurations should increase or inhibit it.

These assumptions can be expressed more explicitly and concretely in a number of notational schemes. For example, the combination of evidence from different sources can be expressed in semantic networks (Anderson, 1976), logogens (Morton, 1969), analyzers (Treisman, 1969), interactive filters (Anderson, 1973), and, possibly, production systems (Anderson, 1976); the accumulation of evidence over time can be modeled as a random walk process (Feller, 1968) to predict detailed properties of reaction time and accuracy data (e.g., Link, 1975; Ratcliff, 1978). This means that models based on these notational schemes should be able to account for facilitation and inhibition in Stroop and priming tasks without changing their assumptions fundamentally or adding special mechanisms. It also means that the assumptions are quite general and can be studied to advantage without unnecessary commitment to a particular notational scheme. A simple model embodying these assumptions is as follows:

Evidence is assumed to accumulate over time in some composite decision process until a threshold is exceeded and a response is emitted. The effects of attention and automaticity are expressed as weights on each of N dimensions of the stimulus situation that reflect the rate at which evidence is gained.[1] Automatic weights are assumed to be constant in sign (facilatory or inhibitory) and magnitude over situations, purposes, and intentions, reflecting their relative permanence. In contrast, attentional weights are assumed to vary in sign and magnitude over situations as purposes and intentions dictate, reflecting their strategic flexibility. In particular, the magnitude of attentional weights is assumed to increase in proportion to cue validity to optimize performance (Logan & Zbrodoff, 1979; for a formal development of an optimal allocation function, see Shaw, 1978). The amount of evidence, E_T, accumulated when the threshold is reached is the sum of the evidence available attentionally and automatically from the N dimensions, including the dimension to be reported, that is,

$$E_T = \sum_{i=1}^{N} E_i. \tag{1}$$

[1] For simplicity, evidence is assumed to increase linearly with time. This assumption provides a reasonable first approximation to more complex growth functions.

The amount of evidence, E_R, to be gained from the reported dimension is the difference between the threshold amount of evidence and the amount available from the unreported dimensions, that is,

$$E_R = E_T - \sum_{i=1}^{N-1} E_i. \tag{2}$$

Evidence from the reported dimension is gained at a constant rate determined by the magnitude of the attentional and automatic weights attached to it (ATT_R and AUT_R, respectively). Reaction time will depend on the time required to accumulate evidence plus some constant time, k, for motor processes, that is,

$$RT = k + (ATT_R + AUT_R)^{-1} \cdot \left(E_T - \sum_{i=1}^{N-1} E_i\right). \tag{3}$$

Thus, evidence from unreported dimensions that is relevant to the appropriate response (i.e., positive evidence) will reduce the amount to be gained from the reported dimension and facilitate reaction time. Evidence from unreported dimensions relevant to an inappropriate response will increase the amount to be gained from the reported dimension and increase or inhibit reaction time.

The amount of evidence an unreported dimension adds to the combined decision process depends on the magnitude of the attentional and automatic weights assigned to it and on the time, t_i, during which the unreported dimension is available to influence the reported one. To express it simply,[2]

$$E_i = (ATT_i + AUT_i) \cdot t_i. \tag{4}$$

Thus, if attentional and automatic weights are held constant, unreported dimensions that are available sooner (i.e., those with larger t_is) will contribute more to the composite decision process and produce more facilitation and inhibition.

[2] On the assumption that each unreported dimension has a threshold that must be exceeded before it adds evidence to the composite decision process, t_i represents the difference between the time at which the threshold was crossed in the unreported dimension and the (average) time at which the threshold was crossed in the composite decision process. It can be estimated by the difference in reaction time between judgements of the reported dimension and judgements of the i^{th} unreported dimension (see Appendix 2). Equation 4 assumes a linear growth in evidence with time, following the linear growth in the expected sum of a random walk (Feller, 1968). The same points could be made with many other growth functions. Indeed, asymptotic growth functions like those described by Wickelgren (1977) and McClelland (1979; e.g., Eq. 14) would be necessary to account for asymptotic levels of facilitation and inhibition observed in the priming paradigm when the prime precedes the target by a half a second or more (e.g., Neely, 1977; Posner & Snyder, 1975b).

The Experiments

Two experiments were conducted to strengthen the empirical parallels drawn between the priming paradigm and the Stroop paradigm and to provide a test of the model. Both experiments used a Stroop-like task in which subjects judged the relative position of a word and an asterisk, reporting whether the asterisk (or word) appeared above or below the word (or asterisk). The words themselves were ABOVE and BELOW, and the word–asterisk configuration appeared above and below a central fixation point. The theoretical issues raised above were examined in four major manipulations.

First, all possible combinations of values of the three dimensions were used, so that both the "absolute" position of the configuration on the screen and the identity of the word it contained could be compatible with or conflict with the required judgment of relative position, and could facilitate or inhibit performance, respectively. Since these effects are believed to be automatic or obligatory, they were expected to occur with equal strength under all experimental conditions. In terms of analysis of variance, the compatibility of absolute position and word identity with relative position should produce main effects in the reaction time data.

Second, the relative frequency of compatible and conflicting trials was varied independently for absolute position and word identity so they both could serve as cues to relative position. When an unreported dimension was a valid cue, it conflicted with the reported dimension on 20 or 80% of the trials. With 20% conflicting trials, the value of relative position was likely to be the same as the value of the unreported dimension, so attention to the unreported dimension should facilitate responses on compatible trials and inhibit them on conflicting trials. With 80% conflicting trials, the value of relative position was likely to be the opposite of the value of the unreported dimension, so attention should facilitate responses on conflicting trials and inhibit them on compatible trials. In both cases, cue validity is the same, but the cueing relations are opposite. In the former case, attention confirms prior associations and should enhance the facilitation and inhibition produced automatically. In the latter case, attention opposes prior associations and should counteract automatic facilitation and inhibition, perhaps reversing the usual Stroop effect (see Logan & Zbrodoff, 1979.) In terms of analysis of variance, the attentional effects for each dimension should produce an interaction between relative frequency of conflicting trials and compatibility in the reaction time data.

Third, since an experiment reported in detail in Appendix 1 had established that under the present conditions information about absolute position was available before information about word identity and information about word identity was available before information about relative position, differences in cue validity effects for absolute position and word identity can provide evidence on the time-course of attentional activation. The attentional effects were expected to be stronger for absolute position, which is available sooner, than for word identity, which is available later. In terms of analysis of variance, the interaction between relative frequency and compatibility should be stronger with absolute position cues than with word identity cues if the parallels drawn between the paradigms are correct.

Fourth, the number of cues valid at one time (1 or 2) was varied between experiments in an initial attempt to assess the nature of capacity limitations in cue utilization. The capacity for attentional activation has often been considered limited, and the limits may influence performance in many ways (LaBerge & Samuels, 1974; Logan, 1979; Neely, 1977; Posner & Snyder, 1975a). The present manipulation allowed investigation of one specific hypothesis, namely, whether or not the "strength" of attention as it is interpreted here (represented in the magnitude of attentional weights) reflects the amount of capacity allocated to a particular dimension or cueing relation. If it does, a cue validity effect may be stronger when one cue is valid than when two are valid since more capacity would be available to it. If it does not, the size of a cue validity effect should be the same no matter how many cues are valid since the different cues do not compete for the same capacity. Thus, interactions between relative frequency and compatability should be stronger with one cue than with two if strength of attention reflects the amount of capacity allocated. Alternatively, the interactions should be of the same order of magnitude with one cue as with two if strength and capacity are not related. The two cues were valid simultaneously in Experiment 1; only one cue was valid at a time in Experiment 2.

EXPERIMENT 1

Method

Subjects. Sixteen undergraduate students from Erindale College participated to fulfill course requirements.

Apparatus and stimuli. The stimuli were configurations of a word and an asterisk. The word was ABOVE or BELOW, the asterisk appeared directly above or below the third letter of the word, and the whole configuration appeared above or below a central fixation point. All possible combinations of these three two-valued dimensions were used, forming a set of eight different stimuli.

The stimuli were displayed on a point-plot cathode-ray tube (Techtronix model 604 equipped with P_{31} phosphor) under the control of a PDP11/03 laboratory computer (Digital Equipment Corporation). Each character, including the asterisk, was formed by illuminating points in a 5×7 dot matrix, and subtended about $.38 \times .57°$ of visual angle when viewed at a distance of 60 cm. Each word subtended about 2.67° horizontally and .57° vertically, and the gap between the word and the asterisk subtended about .19°. The separation between the fixation point and the nearest edge of the configuration subtended about .76°.

Each trial began with a fixation point illuminated in the center of the screen. After 500 msec, it was extinguished and replaced by the word–asterisk configuration for that trial. The configuration remained on the screen until the subject responded, whereupon an intertrial interval began which lasted at least 2.5 sec (the duration varied somewhat due to variable requirements to access the computer's disks between trials). The computer measured reaction time in milliseconds from the onset of the stimulus to the onset of the response, and recorded the response for each trial. Subjects responded by pressing the leftmost and rightmost of a panel of eight buttons with the index fingers of their left and right hands, respectively. They rested their fingers of the buttons between trials, and were left alone in a room with the computer, display system, and response apparatus throughout each block.

Procedure. Subjects were instructed to report the relative position of the word and the asterisk. Half of the subjects responded "above" if the asterisk appeared above the word and "below" otherwise, and half responded "above" if the word was above the asterisk and "below" otherwise. Half of the subjects responding each way pressed the right button to indicate "above" and the left to indicate "below," while the other half did the opposite.

There were four different stimulus types representing the four possible combinations of compatible and conflicting trials defined with respect to each unreported dimension (i.e., compatible–compatible, compatible–conflicting, conflicting–compatible, and conflicting–conflicting). Each stimulus type was represented by two tokens, one to which the correct response was "above" and one to which the correct response was "below." Within stimulus types, each token appeared equally often so that 50% of the appropriate responses would be "above" and 50% would be "below."

Cue validity was manipulated by varying the relative frequency of the different stimulus types. The experiment involved four blocks of 100 trials each, one for each of four cue validity conditions. Since both cues were valid at the same time, the four blocks represented each combination of 20 and 80% position-conflicting trials and 20 and 80% word-conflicting trials (i.e., 20–20, 20–80, 80–20, and 80–80). The relative frequency of conflicting trials was varied independently for each dimension so that each block of 100 trials consisted of 64 trials with the most frequent stimulus type (32 with each token), 16 trials with each of the two intermediate-frequency stimulus type (8 with each token), and 4 trials with the least frequent stimulus type (2 with each token). Subjects received the four blocks in an order determined by a balanced Latin square with four subjects receiving each order. Within block orders, each subject received a different one of the four possible combinations of relative position task (asterisk relative to word vs word relative to asterisk) and response button to response category mapping ("above" on the right vs "above" on the left).

Within the above constraints, the order of stimulus types and tokens within blocks was random. A different random order was prepared for each block for each subject.

Instructions stressed both speed and accuracy. Subjects were shown examples of each stimulus type and token, and were told how to respond appropriately. Once it was clear the subject understood what to do, testing began. Subjects were not told about the frequency manipulation and so had to develop their own expectations from experience. No practice was given. Short breaks were allowed between blocks.

Data analysis. Mean reaction times were computed for each combination of relative frequency and compatibility conditions for each subject, excluding errors and reaction times greater than 1500 msec. These data were subjected to two analysis. The first was a standard four-way analysis of variance (relative frequency of position conflicting × relative frequency of word conflicting × position compatibility × word compatibility), designed to provide a "conventional" description of the data. The second was designed to fit the model to the data. In a manner described fully in Appendix 2, versions of Eq. (3) were derived for each stimulus type for each relative frequency condition. The 16 equations so derived were used to construct a contrast involving the 16 means from each combination of relative frequency and compatibility conditions, which was tested against an error term derived from a one-way analysis of variance on all of the data. Deviations from the model were also tested against the same error term, and the proportion of treatment variance attributable to the model was calculated. Note that this analysis, which expresses condition means as the sum of the deviations from the grand mean produced by automatic and attentional weights on each dimension, is redundant with the standard four-way analysis of variance (i.e., the model asserts that the only significant effects in the four-way analysis will be the main effects of position and word compatibility, the interaction between position compatibility and relative frequency of position-conflicting trials, and the interaction between word compatibility and the relative frequency of word-conflicting trials). The second analysis has the advantage of testing the model against all of the data simultaneously, using only four degrees of freedom (one for each attentional and automatic weight for each dimension), and the fit to the data can be assessed more directly. Moreover, the second analysis can be calculated with estimated effects of attentional and automatic weights from Experiment 2 to assess quantitatively the agreement between experiments.

Results

Standard analysis. Mean reaction times across subjects in each combination of relative frequency and compatibility conditions are displayed in Table 1. Three aspects of the data are relevant. First, the main effects of compatibility for each unreported dimension indicate the extent of automatic processing. Second, the interactions between relative frequency of conflicting trials and compatibility for each dimension indicate the extent to which attention can alter or overcome automatic effects. Third, the relative strength of the interactions between relative frequency and compatibility with position and word cues indicates the time-course of attentional activation. All three effects were apparent in the data and received statistical support, where possible.

Overall, reaction times were significantly slower with absolute position conflicting than with absolute position compatible, $F(1,15) = 9.97$, $p < .01$, and were also significantly slower with word identity conflicting than with word identity compatible, $F(1,15) = 19.21$, $p < .01$. These effects varied in magnitude with the relative frequency of conflicting trials. With position cues, compatible reaction times were 111-msec faster than conflicting ones when conflicting stimuli were relatively rare (20%) but were 23-msec slower than conflicting ones when conflicting stimuli were relatively frequent (80%), reversing the usual Stroop effect. Eleven out of 16 subjects showed the reversal, and all 16 showed a smaller compatibility effect with conflicting trials frequent. In the group data, the interaction between relative frequency of position-conflicting trials and position compatibility was highly significant, $F(1,15) = 53.76$, $p < .01$. It is displayed in the left panel of Fig. 1.

With word cues, compatible reaction times were 60-msec faster than conflicting ones when conflicting stimuli were relatively rare, but the difference dropped to 16-msec when conflicting stimuli were relatively frequent. Thirteen out of 16 subjects showed a small compatability effect

TABLE 1

Observed and Predicted Reaction Times and Error Rates in Experiment 1[a]

Compatibility condition		Cueing condition							
		20–20		20–80		80–20		80–80	
		Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
PW	RT	518	509	525	530	571	576	581	596
	Error	.005		.020		.031		.016	
$P\bar{W}$	RT	.573	569	534	548	663	636	615	615
	Error	.027		.024		.125		.035	
$\bar{P}W$	RT	625	620	646	641	560	553	572	574
	Error	.043		.141		.021		.031	
$\bar{P}\bar{W}$	RT	661	681	664	660	620	614	588	593
	Error	.078		.063		.059		.040	

[a] 20 and 80 are percent conflicting trials: the first number for position cues, the second for word cues; P = position compatible, $\bar{P}$ = position conflicting, W = word compatible, and $\bar{W}$ = word conflicting.

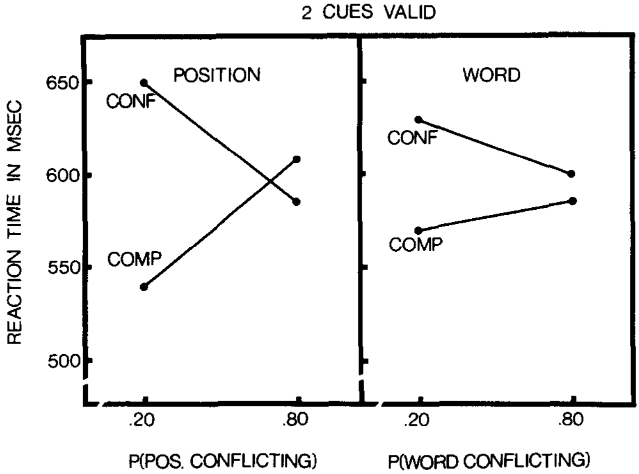

FIG. 1. Mean reaction time as a function of the probability of conflicting trials for each unreported dimension in Experiment 1 (compatible vs conflicting trials is the parameter).

when conflicting trials were relatively frequent, and two of the 13 showed a reversal. In the group data, the interaction between relative frequency of word-conflicting trials and word compatibility was significant $F(1,15) = 8.79, p < .01$, and is displayed in the right panel of Fig. 1.

The only other significant effect in the analysis was the interaction between position compatibility and relative frequency of word-conflicting trials, $F(1,15) = 5.14, p < .05$. It indicates that reaction times to position-compatible stimuli were faster when word-conflicting trials were relatively rare, while reaction times to position-conflicting stimuli were not affected. This interaction was not expected and has no ready explanation.

The error rates, displayed in Table 1, reflect the major trends in the reaction time data. Note that error rates were relatively low, even in conditions with the lowest relative frequencies.

Fitting the model. Mean reaction times predicted from a derivation of Eq. (3) also appear in Table 1. The effects of attentional weights were estimated as 33.46 msec for position information and 10.41 msec for word information; the effects of automatic weights were estimated as 22.29 msec for position information and 19.86 msec for word information.

Deviations from the grand mean predicted by the model were used to construct a linear contrast to assess the model's fit. The effects due to the model were significant, $F(4,225) = 18.15, p < .01$, and accounted for 94.57% of the total treatment variance. Deviations from the model were not significant, $F(11,225) < 1$, and accounted for 5.43% of the total treatment variance.

To assess agreement with Experiment 2, the effects estimated from Experiment 2 were used to calculate predictions for Experiment 1. Generally, the deviations from the mean predicted from Experiment 2 underestimated the deviations predicted from Experiment 1 (in 12 out of 16 cases), but the fit was relatively good: The linear contrast constructed with the deviations predicted from Experiment 2 was significant, $F(4,225) = 17.61, p < .01$, and accounted for 91.8% of the total treatment variance. Deviations from the model were not significant, $F(11,225) < 1$, and accounted for 8.2% of the total treatment variance.

Discussion

This experiment was successful in demonstrating automatic effects, in the form of main effects of compatibility for each dimension, which were modulated by attentional effects, in the form of interactions between relative frequency and compatibility for each dimension. The automatic effects are consistent with several experiments in the literature (e.g., Palef, 1978; Palef & Olson, 1975; also see Appendix 1). The attentional effects resemble those of Logan and Zbrodoff (1979) and extend the generality of their results.

A major purpose of this experiment was to provide evidence on the time-course of attentional activation, and indeed, attentional effects seemed stronger with position cues, which were available sooner, than with word cues, which were available later. While it is not possible to construct a contrast to evaluate this effect statistically, it is reasonably clear in the data displayed in Fig. 1: With position cues, attentional effects were strong enough to reverse the compatibility effect, whereas with word cues they were not. (Position and word compatibility main effects were about the same at 44 and 38 msec, respectively.) Similar trends are apparent in the individual data; more subjects reversed the compatibility effect with position cues than with word cues. Thus, in the Stroop paradigm as in the priming paradigm the effectiveness of a valid cue is determined by the time at which it becomes available.

The absence of significant higher-order interactions in the standard analysis, and equivalently, the absence of significant deviations from the model in the second analysis, are noteworthy since they suggest that subjects were able to use the two cues independently. This is particularly remarkable considering that subjects changed cueing conditions and had to adopt a new attentional set every 6 or 7 min (500-msec warning interval, plus 600-msec reaction time, plus 2.5-sec intertrial interval, times 100 trials). Clearly, we are not dealing with gradual changes in attentional habits (cf, Logan, 1979; Shiffrin & Schneider, 1977), but rather with rapid strategic adjustments.

EXPERIMENT 2

The second experiment was a replication of the first except that only one cue was valid at a time. Whereas in Experiment 1, the frequency of conflicting trials was different from 50% for both unreported dimensions in each block (i.e., both cues were valid), in Experiment 2, the percentage of conflicting trials differed from 50% for one unreported dimension (the valid one) and was fixed at 50% for the other (the invalid one) in each block. This provides an opportunity to observe automatic effects, attentional effects, and evidence on the time-course of attentional activation under different circumstances, and to begin to assess the extent of capacity limitations in cue utilization. In particular, if the "strength" of attention to a particular dimension reflects the amount of capacity allocated to it, cueing effects should be much stronger in Experiment 2 than in Experiment 1 since more capacity should be available to strengthen attentional links with only one cue valid. Alternatively, if the strength of attention is not related to capacity, the cueing effects in Experiment 2 should be no stronger than those observed in Experiment 1.

Method

Subjects. Sixteen undergraduate students from Erindale College participated to fulfill course requirements. None had served in Experiment 1.

Apparatus and stimuli. These were the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1 except that only one cue was valid at a time. Again, there were four stimulus types, each represented by two equally-frequent tokens, and cue validity was manipulated by varying the relative frequency of conflicting trials. When a dimension was not valid, relative frequency was held constant at 50%; when a dimension was valid, relative frequency was either 20 or 80%. There were four blocks of 100 trials, one block for each of the following cue validity conditions: (1) 20% position conflicting and 50% word conflicting trials, (2) 80% position conflicting and 50% word conflicting trials, (3) 50% position conflicting and 20% word conflicting trials, and (4) 50% position conflicting and 80% word conflicting trials. The relative frequency of conflicting trials was varied independently for each dimension so that each block of 100 trials involved 40 with each of the two more frequent stimulus types (20 with each token) and 10 with each of the two less frequent stimulus types (5 with each token).

Each subject completed two blocks with one cue valid before experiencing a block with the other cue valid. For half of the subjects, absolute position was valid before word identity, while for the other half, word identity was valid before absolute position. With each cue, half of the subjects received the 20% condition before the 80% condition, and half received the 80% condition before the 20% condition. Assignment to orders of relative frequency conditions (20 vs 80%) was orthogonal to the assignment to orders of cue conditions (position valid first vs word valid first). Both were orthogonal to the assignment to relative position tasks (asterisk relative to word vs word relative to asterisk) and to the assignment of response buttons to response categories ("above" on the right vs "above" on the left), which were orthogonal to each other.

The order of stimulus types and tokens within blocks was random, within the above constraints, and a separate random order was prepared for each subject. Subjects were instructed, practiced, and rested as in Experiment 1.

Data analysis. Mean reaction times were computed for each combination of frequency and compatibility conditions for each subject excluding errors and reaction times greater than 1500 msec. These scores were subjected to two analyses. The first was a standard four-way analysis of variance (position valid vs word valid × relative frequency ×

position compatibility × word compatibility) designed to provide a "conventional" description of the data. The second was designed to fit the model to the data, using the procedure described in Appendix 2. Note that the second analysis assessed the model more directly (i.e., with fewer degrees of freedom) than the first, standard analysis. The second analysis involves 4 degrees of freedom, 1 for each automatic and attentional effect for each dimension. In the standard analysis, these effects appear in the main effects of position and word compatibility, the interactions between relative frequency and compatibility, and the interactions between position-vs-word valid, relative frequency, and compatibility, totaling 6 degrees of freedom.

Results

Standard analysis. Mean reaction times across subjects in each combination of relative frequency and compatibility conditions are displayed in Table 2.

Overall, reaction times were slower with position conflicting than with position compatible, $F(1,15) = 25.56, p < .01$, and were slower with word conflicting than with word compatible, $F(1,15) = 14.59, p < .01$. These effects varied with the dimension that was valid and with the relative frequency of conflicting trials within the valid dimension. When position cues were valid, position-compatible reaction times were 92-msec faster than position-conflicting ones when conflicting stimuli were relatively rare (20%), but were only 7-msec slower than position-conflicting ones when conflicting stimuli were relatively frequent (80%). This reversal of the compatibility effect was apparent in the data of 9 of the 16 subjects; 15 of the 16 showed a smaller compatibility effect when conflicting trials were frequent. In the group data, those effects produced significant interactions between relative frequency and position compatibility, $F(1,15) = 55.63, p < .01$ and between position-vs-word-valid, relative frequency, and position compatibility, $F(1,15) = 14.78$, $p < .01$. The interaction between relative frequency and position compatibility with position cues valid is displayed in the left panel of Fig. 2.

When words were valid cues, word-compatibile reaction times were 38-msec faster than word-conflicting ones when conflicting trials were relatively rare, but the difference dropped to 15 msec when conflicting trials were relatively frequent. Ten of the 16 subjects showed a smaller compatibility effect when conflicting trials were relatively rare, and five of those showed a reversal. In the group data, the interaction between position-vs-word-valid, relative frequency, and word compatibility approached conventional levels of statistical significance, $F(1,15) = 4.34, p < .06$. The interaction between relative frequency and word compatibility with word cues valid is displayed in the right panel of Fig. 2.

In this analysis the relative strength of attentional effects with position and word cues could be assessed directly. A contrast, comparing the relative frequency × position compatibility interaction with position cues

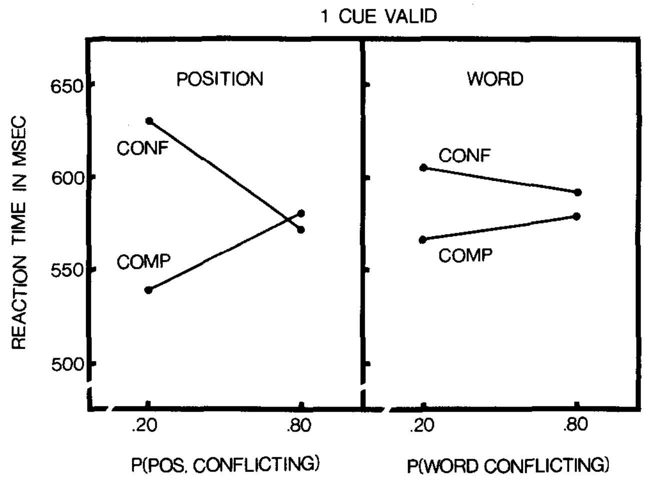

FIG. 2. Mean reaction time as a function of the probability of conflicting trials when each unreported dimension is valid in Experiment 2 (compatible vs conflicting trials in the parameter).

valid with the relative frequency × word compatibility interaction with word cues valid, was significant, $F(1,15) = 13.45$, $p < .01$, indicating stronger effects with position cues valid.

The only other significant effect in the analysis was the interaction between position compatibility and word compatibility, $F(1,15) = 4.60$, $p < .05$, reflecting an overall advantage for stimuli that were both position compatible and word compatible.

The error rates, displayed in Table 2, were relatively low and reflected the major trends in the reaction time data.

Fitting the model. Mean reaction times predicted from the model also appear in Table 2. In this experiment, the effects of attentional weights were estimated as 24.7 msec for position information and 5.73 msec for word information; the effects of automatic weights were 22.5 msec for position information and 13.09 msec for word information.

Deviations from the grand mean predicted by the model were used to construct a linear contrast to assess the model's fit. The effects due to the model were significant, $F(4,225) = 17.30$, $p < .01$ and accounted for 94.96% of the total treatment variance. Deviations from the model were not significant, $F(11,225) < 1$, and accounted for 5.03% of the total treatment variance.

To assess agreement with Experiment 1, the effects in Experiment 1 were used to calculate predictions for Experiment 2. Generally, the deviations from the mean predicted from Experiment 1 tended to overestimate the deviations predicted from Experiment 2 (in 10 out of 16 cases)

TABLE 2

Observed and Predicted Reaction Times and Error Rates in Experiment 2[a]

Compatibility condition		Cueing condition 20−50 Observed	20−50 Predicted	80−50 Observed	80−50 Predicted	50−20 Observed	50−20 Predicted	50−80 Observed	50−80 Predicted
PW	RT	.529	523	559	572	537	542	554	553
	Error	.018		.075		.017		.038	
$P\bar{W}$	RT	.549	549	598	598	579	579	579	568
	Error	.030		.069		.044		.027	
$\bar{P}W$	RT	625	617	556	568	597	588	602	598
	Error	.063		.025		.039		.050	
$\bar{P}\bar{W}$	RT	637	643	588	594	631	624	607	613
	Error	.075		.023		.075		.034	

[a] 20, 50, and 80 are percent conflicting trials: the first number for position cues, the second for word cues; P = position compatible, $\bar{P}$ = position conflicting, W = word compatible, and $\bar{W}$ = word conflicting.

and predicted deviations in the opposite direction in two cases [conditions (10) and (11)], but again, the fit was relatively good: The linear contrast constructed with the deviations predicted from Experiment 1 was significant, [$F(4,225) = 16.69, p < .01$], and accounted for 91.62% of the total treatment variance. Deviations from the model were not significant, [$F(11,225) < 1$], and accounted for 8.38% of the total treatment variance.

Discussion

This experiment was successful in demonstrating automatic and attentional effects which were consistent with previous findings (Experiment 1; Logan & Zbrodoff, 1979; Palef, 1978). It also addressed the time-course of attentional activation, and once again, the results were clear: Attentional effects were significantly stronger with position cues, which were available sooner, than with word cues, which were available later. These effects are apparent in the data displayed in Fig. 2 and in data from individual subjects (i.e., more subjects showed a smaller compatibility effect in the 80% condition with position cues than with word cues). Thus Experiment 2 provides additional evidence that the effectiveness of a cue is determined by the time at which it becomes available as well as its validity. The parallels drawn between the priming paradigm and the Stroop paradigm seem well-founded.

A second purpose of this experiment was to assess the nature and extent of capacity limitations in cue utilization. Only one cue was valid at a time in this experiment, whereas two cues were valid simultaneously in Experiment 1. If the number of cueing relations that can be attended at once is limited, cue validity effects should be stronger in this experiment than they were in Experiment 1. Clearly, this was not the case. If anything, the interactions between frequency and compatibility were weaker in Experiment 2 than in Experiment 1 (compare Figs. 1 and 2; also, compare the number of subjects showing the effects in each experiment). These results support the conclusion that cue utilization is not capacity limited (also see LaBerge et al., 1977), and resemble the more general finding that attention can be divided between separate stimulus dimensions with no loss in performance (e.g., Allport, 1971; Treisman, 1969). The generality of the conclusion with respect to cue utilization is important and warrants further investigation. In particular, it would be useful to determine limits on the number of cues that can be used simultaneously and to discover factors affecting the limit. Further, a more sensitive within-subject design would be desireable.

GENERAL DISCUSSION

The experiments reported here have shown that automatic effects in the Stroop paradigm can be altered and overcome by attention, and that attentional effects are limited by the time at which the relevant cues become available. Parallel effects have been observed in the priming paradigm (e.g., Neely, 1977), suggesting that the two paradigms have much in common. This conclusion has two important implications for studies in the Stroop paradigm.

First, the finding that facilitation and inhibition may result from attentional processing as well as automatic processing may challenge the interpretation of experiments done previously. Most Stroop studies have assumed automatic facilitation and inhibition without considering the possibility of attentional effects. The present findings, and those of Logan and Zbrodoff (1979), suggest that attentional effects are possible whenever stimulus frequencies are not equal. Thus, all studies with inequal frequencies are open to an attentional interpretation. However, the boundary conditions of attentional effects are not well established (e.g., to what extent do they vary with the number of stimulus–response alternatives, etc.), and it may be best to reserve judgment until more is known.

Second, the parallels with the priming paradigm suggest that the usual interpretation of Stroop effects in terms of automatic processing alone fails to appreciate the scope of the paradigm and may restrict unduly the range of questions the paradigm is used to answer. The priming paradigm has been useful in investigating invariant and novel aspects of cognitive structure, for example, the nature of concepts in semantic memory (Rosch, 1975) on the one hand, and the representation of events in episodic memory (Ratcliff & McKoon, 1978) on the other. It has been useful in investigating strategy-dependent (Neely, 1977) and strategy-invariant (LaBerge, 1973; LaBerge et al., 1977) effects, and in investigating the "dynamics" of attentional and automatic effects (Posner & Snyder, 1975b). The parallels suggest that these effects are possible in the Stroop paradigm as well, and motivate a broader scope of inquiry. The two paradigms permit different but complementary perspectives on the apprehension of relations between aspects of the environment; the picture begun with the study of relations between stimuli in the priming paradigm may be completed with the study of relations within stimuli in the Stroop paradigm.

The general model outlined in the Introduction has four features which warrant further investigation and development. First, it provides a plausible qualitative account of the parallels drawn between the priming paradigm and the Stroop paradigm, and a particular version of the model showed good quantitative agreement with the two Stroop experiments reported here. The model argues that the different stimulus situations characteristic of the two paradigms have the same effect on a composite decision process (i.e., they both provide a temporally extended blend of evidence from past associations and current contingencies) and so should have the same effect on performance. This feature should be expressed in a theoretical notation that deals with representation more explicitly.

Second, the model argues that in both paradigms facilitation and inhibition are consequences of the same process (i.e., the composite decision) and do not require separate explanations. This feature could be tested profitably in a dual-task experiment, comparing dual-task interference observed on facilitation and inhibition trials. Assuming that evidence accumulates over time automatically (see Logan, 1978), the model predicts no more dual-task interference on inhibition trials than on facilitation trials (since the same process is involved in both cases). By contrast, models that posit extra processing mechanisms to deal with inhibition trials (e.g., a contingent threshold adjustment or rechecking operation; see Clark & Brownell, 1975; Palef, 1978) should predict more dual-task interference on inhibition trials. Indeed, there is some evidence that facilitation and inhibition trials produce equivalent dual-task interference (see Logan, 1978, Expt. 1).

Third, the model argues that attention dominates the effects of automatic processes (by adding evidence to the decision process) without affecting their functioning. The simple version assumed that attentional and automatic effects combined additively, and the goodness of fit suggests that this assumption is warranted, at least in the experiments reported here. This is not to say that attention cannot ultimately change automatic processes, since such effects clearly exist (e.g., Logan, 1979; Shiffrin & Schneider, 1977); rather, the model suggests that the short-term effects of attention have a negligible effect on existing automatic processes. More detailed studies of the process of automatization would provide valuable information.

Fourth, the model argues that perceptual competition and response competition, which are generally regarded as adversary explanations of the Stroop effect (e.g., Dyer, 1973), are special cases subsumed by the composite decision process. The assumption that evidence from different sources is combined entails no assumption of a fixed information flow through a succession of stages; the different sources may be processed in parallel, subject only to the constraint that sources available sooner can influence (speeded) decisions about sources that become available later, but not vice versa.

Clearly, other models are available to account for Stroop and priming effects and for the parallels drawn between them (for reviews, see Dyer, 1973; Posner, 1978). Indeed, in the Introduction I have suggested directions along which more explicit models might be developed. The point is to develop models that are broad enough and rich enough to account for the major effects and the parallels in a clear and straightforward manner, without having to add special mechanisms for particular effects.

What remains to be investigated is the process by which current contingencies are incorporated into the decision process. It is important in the present context because it may distinguish the Stroop and priming paradigms. In priming tasks, a number of contingencies are valid in the same block of trials (e.g., Neely, 1977; Posner & Snyder, 1975b), and the prime indicates which one will apply on the current trial. This contingency must be incorporated into the decision process (i.e., as an attentional weight) and there is evidence that this requires 200–500 msec between stimulus onsets (Neely, 1977; Posner & Snyder, 1975b). In most versions of the Stroop task, there is not enough time to construct attentional weights representing the contingencies between dimensions. Indeed, in the Stroop experiments that demonstrated attentional effects (Expts. 1 and 2; Logan & Zbrodoff, 1979), 100–200 msec elapsed between the finishing times of the reported and unreported dimensions. Thus, in the Stroop paradigm, attentional weights are probably constructed in advance of stimulation. This suggests that the number and variety of contingencies that can affect performance may be more constrained in the Stroop paradigm than in the priming paradigm.[3]

The process by which current contingencies are incorporated into the decision process is important more generally, since it is equivalent in some respects to the process by which instructions are understood. In both cases, cues from the environment result in a new organization of existing cognitive structures, designed to enable the performance of a particular task. Developing a theory of how instructions are understood is a major project of tremendous theoretical and practical importance, both in the laboratory and in the real world. Possibly, the Stroop and priming tasks may provide a microcosm in which to study it.

CONCLUSIONS

The experiments have shown that attention may be divided between the dimensions of a Stroop stimulus if the unreported dimensions convey information about the reported ones, and that the effects of attending to an unreported dimension are stronger the sooner the dimension becomes available. These findings resemble general findings in the priming paradigm: attention is paid to aspects of the stimulus situation that are not reported (i.e., the prime), and the effects of attending to the prime are stronger the sooner it becomes available. The results of the experiments and the parallels with the priming paradigm can be explained by a composite decision model that combines evidence from several sources.

[3] For example, subjects could not be prepared for compatible and conflicting Stroop stimuli at the same time and show facilitation (since the weights would be opposite in sign and should cancel each other out). However, facilitation might be observed if a cue indicating whether dimensions will be compatible or conflict were presented some time before the Stroop stimulus. (I have some unpublished data showing this to be the case.)

APPENDIX 1: PROCESSING TIMES FOR EACH DIMENSION

The logic of Experiments 1 and 2 requires that absolute position is processed faster than word identity and that word identity is processed faster than relative position. Although there is evidence supporting these points in the literature (e.g., Palef, 1978; Palef & Olson, 1975), it was important to establish them empirically in the stimulus situation used in Experiments 1 and 2. The experiment reported here was designed to do so.

Subjects performed three tasks, reporting each dimension of the stimuli, under conditions in which no unreported dimension was a valid cue to the reported one. In each task, the word–asterisk configuration was separated from the fixation point by two visual angles ("wide" and "narrow") in an attempt to vary the discriminability of the different dimensions. In particular, wide spacing was expected to facilitate absolute position judgments (since wide separations are more discriminable; Clark & Brownell, 1975) and impair word identity judgments (since widely-spread words would fall on less sensitive regions of the retinae).

Method

Subjects. Twelve undergraduate students and laboratory staff from Erindale College volunteered their services. None had served in Experiments 1 and 2.

Apparatus and stimuli. These were the same as in Experiments 1 and 2, except for the spacing manipulation. In the wide spacing condition, the separation between the fixation point and the nearest edge of the word–asterisk configuration was .76°, as in Experiments 1 and 2. In the narrow spacing condition, the separation was .38°.

Procedure. Each subject completed three tasks, *"absolute" position,* in which the position of the configuration relative to the fixation point was reported, *word identity,* in which the word the configuration contained was reported, and *relative position,* in which the position of the asterisk relative to the word (or vice versa) was reported. Each subject received six blocks of 72 trials, one for each combination of tasks and spacing conditions (wide vs narrow).

The orders of conditions were balanced as follows: As in Experiments 1 and 2, there were two versions of the relative position taks (asterisk relative to word and word relative to asterisk), and half of the subjects performed each version. Within those groups, each subject received the three tasks in a different order, one subject receiving each of the six possible orders. Half of the subjects in each group received wide spacing before narrow, while the other half received the opposite. Spacing conditions were nested within tasks so that each subject performed one task with both wide and narrow spacing before moving on to the next. Orders of tasks and spacing conditions were balanced by dividing the six possible orders of tasks into two 3 × 3 Latin squares, and assigning one order of spacing conditions to each square.

In each task every subject pressed the right button to indicate "above" and the left to indicate "below."

Each task involved four different stimulus types representing the four possible combinations of compatible and conflicting trials defined with respect to each unreported dimension. Since no dimension was to be a valid cue to any other, each stimulus type appeared equally often (18 times each 72-trial block). The order of stimulus types and tokens within blocks was random, and a separate random order was prepared for each block for each subject. Instructions were the same as in Experiments 1 and 2 except that three tasks were described instead of one.

Results

Mean reaction times were computed for each combination of spacing conditions and compatibility conditions for each task for each subject, excluding errors and reaction times greater than 1500 msec. The means across subjects appear in Table 3.

As expected, reaction times were faster in the absolute position task than in the word task, and faster in the word task than in the relative position task. In contrast, the effect of spacing was negligible. These observations were supported in an analysis of variance performed on the data collapsed across compatibility conditions (i.e., tasks × spacing). The main effect of tasks was highly significant, $F(2,22) = 52.68, p < .01$, but neither the main effect of spacing $F(1,11) = 1.72$, nor the interaction between tasks and spacing, $F(2,22) = 1.34$, approached significance.

Compatibility effects within tasks were assessed by separate analyses of variance (i.e., compatibility of dimension 1 × compatibility of dimension 2 × spacing). In the absolute position task, compatibility of relative position had no effect, $F(1,11) < 1$, but reaction times were slower with conflicting words than with compatible ones, $F(1,11) = 10.18, p < .01$. The data in Table 3 suggest that word compatibility effects occurred only in the wide spacing condition, but the spacing × word compatibility interaction was not significant, $F(1,11) = 3.46, p < .10$.

In the word task, relative position compatibility had no effect, $F(1,11) = 1.01$, but reaction times were considerably slower with conflicting absolute positions than with compatible ones, $F(1,11) = 18.51, p < .01$.

In the relative position task, absolute position compatibility had a

TABLE 3
Mean Reaction Times and Error Rates in Wide and Narrow Spacing Conditions of Each Task in the Calibration Study[a]

Compatibility condition		Unreported dimension: W–R Wide	W–R Narrow	P–R Wide	P–R Narrow	P–W Wide	P–W Narrow
$C-C$	*RT*	433	451	572	549	596	579
	Error	.019	.023	.032	.023	.051	.037
$C-\bar{C}$	*RT*	443	454	558	555	616	606
	Error	.014	.037	.042	.051	.060	.042
$\bar{C}-C$	*RT*	461	450	614	577	659	624
	Error	.046	.046	.079	.069	.051	.056
$\bar{C}-\bar{C}$	*RT*	450	448	598	584	658	636
	Error	.028	.037	.069	.060	.120	.065

[a] The first compatibility condition refers to the first dimension, the second compatibility condition refers to the second dimension; C = compatible, $\bar{C}$ = conflicting, P = absolute position, W = word identity, R = relative position).

strong effect, $F(1,11) = 20.22$, $p < .01$, and there was a tendency for reaction times to be slower with conflicting words than with compatible words, but the effect was not significant, $F(1,11) = 2.69$, $p > .10$.

The error rates, displayed in Table 3, reflect the major trends in the reaction time data.

Discussion

This experiment demonstrated that under the conditions of Experiments 1 and 2, absolute position is processed faster than word identity and that word identity is processed faster than relative position. Thus, the assumptions made earlier about relative processing times appear warranted.

The compatibility effects in the three tasks are largely consistent with Palef and Olson's (1975) empirical rule, buttressed by assumptions of varying associative strength. At first glance, the word compatibility effect in the absolute position task and the lack of a word compatibility effect in the relative position task appear to contradict the rule, since word identity should not be available soon enough to influence absolute position judgments but should be available in time to influence relative position judgments. However, it is likely that there was variability in the processing times for each dimension so that the effect in the absolute position task reflects those occasions on which word identity was available before absolute position, and the lack of an effect in the relative position task reflects a preponderance of occasions on which relative position was available before word identity. Analysis of reaction time distributions suggested that the probability that word identity would finish before absolute position was .223 and .271 for wide and narrow spacing, respectively, and that the probability that relative position would finish before word identity was .434 and .417 for wide and narrow spacing, respectively.[4] With the additional assumption that word identity is more strongly associated with absolute position than with relative position, the Palef–Olson rule may be stretched to accommodate the present results.

APPENDIX 2: PREDICTING REACTION TIME

As a preliminary evaluation of the model, mean reaction times in each condition of Experiments 1 and 2 were predicted from estimates of attentional and automatic weights assigned to each unreported dimension.

[4] Probabilities were estimated by sorting reaction times into 25-msec "bins" regardless of compatibility condition or accuracy, and applying the formula $p(\text{overlap}) = \sum_{i=1}^{56} (p(\text{slower}_i) \sum_{j=i}^{56} p(\text{faster}_j))$, where "faster" and "slower" refer to absolute position and word identity, respectively, in one case, and to word identity and relative position, respectively, in the other, and i and j refer to one of the 56 bins from 100- to 1500-msec.

Equation (3) could not be fitted to the data directly because it was not possible to separate the time, k, for motor processes from the time for accumulation of evidence. Instead, Eqs. (3) and (4) were manipulated to express reaction time in each condition as a deviation from the grand mean, and these expressions were used to estimate the effects of attentional and automatic weights and to predict reaction time: Setting $\alpha = (ATT_R + AUT_R)^{-1}$, substituting Eq. (4) into Eq. (3), and expanding.

$$RT = k + \alpha \cdot E_T - \alpha \cdot ATT_p \cdot t_p - \alpha \cdot AUT_p \cdot t_p - \alpha \cdot ATT_w \cdot t_w - \alpha \cdot AUT_w \cdot t_w, \tag{5}$$

where the subscripts p and w refer to position and word information, respectively. In Eq. (5), $k + \alpha \cdot E_T$ represents the grand mean reaction time, and each of the other terms represents a deviation from the grand mean reflecting the attentional or automatic influence of an unreported dimension.

Table 4 contains versions of Eq. (5) for each condition of Experiment 1. These equations were constructed by considering evidence from an unreported dimension to be positive if the unreported dimension was compatible with the reported one, and negative if the unreported dimension conflicted with the reported one (note that α and t_i have been absorbed into ATT_i and AUT_i so that the latter now represent the effects of weights in msec rather than weights themselves). These equations can be used to estimate the effects of weights as follows: The effect of attentional weight on position information is

$$\begin{aligned} ATT_p &= [(3) + (4) + (7) + (8) + (9) + (10) + (13) + (14) \\ &\quad - (1) - (2) - (5) - (6) - (11) - (12) - (15) - (16)] \cdot 16^{-1} \\ &= 33.46. \end{aligned}$$

where (1), (2), . . . represent mean reaction times from the conditions indicated in Table 4. The effect of automatic weight on absolute position is

$$\begin{aligned} AUT_p &= [(3) + (4) + (7) + (8) + (11) + (12) + (15) + (16) \\ &\quad - (1) - (2) - (5) - (6) - (9) - (10) - (13) - (14)] \cdot 16^{-1} \\ &= 22.29. \end{aligned}$$

The effect of attentional weight on word information is

$$\begin{aligned} ATT_w &= [(2) + (4) + (5) + (7) + (10) + (12) + (13) + (15) \\ &\quad - (1) - (3) - (6) - (8) - (9) - (11) - (14) - (16)] \cdot 16^{-1} \\ &= 10.41. \end{aligned}$$

and the effect of automatic weight on word information is

$$\begin{aligned} AUT_w &= [(2) + (4) + (6) + (8) + (10) + (12) + (14) + (16) \\ &\quad - (1) - (3) - (5) - (7) - (9) - (11) - (13) - (15)] \cdot 16^{-1} \\ &= 19.86. \end{aligned}$$

TABLE 4
Versions of Eq. (5) for each Condition of Experiment 1[a]

Frequency condition	Compatibility condition	Eq. (5)	
20–20	PW	$RT = \bar{x} - ATT_p - AUT_p - ATT_w - AUT_w$	(1)
	$P\bar{W}$	$RT = \bar{x} - ATT_p - AUT_p + ATT_w + AUT_w$	(2)
	$\bar{P}W$	$RT = \bar{x} + ATT_p + AUT_p - ATT_w - AUT_w$	(3)
	$\bar{P}\bar{W}$	$RT = \bar{x} + ATT_p + AUT_p + ATT_w + AUT_w$	(4)
20–80	PW	$RT = \bar{x} - ATT_p - AUT_p + ATT_w - AUT_w$	(5)
	$P\bar{W}$	$RT = \bar{x} - ATT_p - AUT_p - ATT_w + AUT_w$	(6)
	$\bar{P}W$	$RT = \bar{x} + ATT_p + AUT_p + ATT_w - AUT_w$	(7)
	$\bar{P}\bar{W}$	$RT = \bar{x} + ATT_p + AUT_p - ATT_w + AUT_w$	(8)
80–20	PW	$RT = \bar{x} + ATT_p - AUT_p - ATT_w - AUT_w$	(9)
	$P\bar{W}$	$RT = \bar{x} + ATT_p - AUT_p + ATT_w + AUT_w$	(10)
	$\bar{P}W$	$RT = \bar{x} - ATT_p + AUT_p - ATT_w - AUT_w$	(11)
	$\bar{P}\bar{W}$	$RT = \bar{x} - ATT_p + AUT_p + ATT_w + AUT_w$	(12)
80–80	PW	$RT = \bar{x} + ATT_p - AUT_p + ATT_w - AUT_w$	(13)
	$P\bar{W}$	$RT = \bar{x} + ATT_p - AUT_p - ATT_w + AUT_w$	(14)
	$\bar{P}W$	$RT = \bar{x} - ATT_p + AUT_p + ATT_w - AUT_w$	(15)
	$\bar{P}\bar{W}$	$RT = \bar{x} - ATT_p + AUT_p - ATT_w + AUT_w$	(16)

[a] 20 and 80 refer to percent conflicting trials: the first number refers to position-conflicting trials and the second to word-conflicting trials; P and $_p$ = position information; W and $_w$ = word information; $\bar{x}$ is the grand mean; and ATT_i and AUT_i are the attentional and automatic effects, respectively, for dimension i.

These effects were used to predict mean reaction time in each condition of Experiment 1 by adding and subtracting them from the grand mean according to the scheme in Table 4. The predicted reaction times are presented with the observed reaction times in Table 1. The predicted deviations from grand mean were used to construct a linear contrast which was used to test the fit of the model in the manner described in the Data Analysis section of Experiment 1.

Table 5 contains versions of Eq. (5) for each condition of Experiment 2. Note that since only one cue was valid at a time, there is only one attentional effect in each condition. The equations in Table 5 were used to estimate the effects of attentional and automatic weights for each dimension as follows: The effect of attentional weight on absolute position is

$$\begin{aligned} ATT_p &= \left[(3) + (4) + (5) + (6) - (1) - (2) - (7) - (8)\right] \cdot 8^{-1} \\ &= 24.70. \end{aligned}$$

where (3), (4) . . . now represent means from conditions indicated in Table 5. The effect of automatic weight on absolute position is

$$\begin{aligned} AUT_p &= \big[(3) + (4) + (7) + (8) + (11) + (12) + (15) + (16) \\ &\quad - (1) - (2) - (5) - (6) - (9) - (10) - (13) - (14)\big] \cdot 16^{-1} \\ &= 22.50. \end{aligned}$$

TABLE 5
Versions of Eq. (5) for Each Condition of Experiment 2[a]

Frequency condition	Compatibility condition	Eq. (5)	
20–50	PW	$RT = \bar{x} - ATT_p - AUT_p - AUT_w$	(1)
	$P\bar{W}$	$RT = \bar{x} - ATT_p - AUT_p + AUT_w$	(2)
	$\bar{P}W$	$RT = \bar{x} + ATT_p + AUT_p - AUT_w$	(3)
	$\bar{P}\bar{W}$	$RT = \bar{x} + ATT_p + AUT_p + AUT_w$	(4)
80–50	PW	$RT = \bar{x} + ATT_p - AUT_p - AUT_w$	(5)
	$P\bar{W}$	$RT = \bar{x} + ATT_p - AUT_p + AUT_w$	(6)
	$\bar{P}W$	$RT = \bar{x} - ATT_p + AUT_p - AUT_w$	(7)
	$\bar{P}\bar{W}$	$RT = \bar{x} - ATT_p + AUT_p + AUT_w$	(8)
50–20	PW	$RT = \bar{x} - AUT_p - ATT_w - AUT_w$	(9)
	$P\bar{W}$	$RT = \bar{x} - AUT_p + ATT_w + AUT_w$	(10)
	$\bar{P}W$	$RT = \bar{x} + AUT_p - ATT_w - AUT_w$	(11)
	$\bar{P}\bar{W}$	$RT = \bar{x} + AUT_p + ATT_w + AUT_w$	(12)
50–80	PW	$RT = \bar{x} - AUT_p + ATT_w - AUT_w$	(13)
	$P\bar{W}$	$RT = \bar{x} - AUT_p - ATT_w + AUT_w$	(14)
	$\bar{P}W$	$RT = \bar{x} + AUT_p + ATT_w - AUT_w$	(15)
	$\bar{P}\bar{W}$	$RT = \bar{x} + AUT_p - ATT_w + AUT_w$	(16)

[a] 20, 50, and 80 refer to percent conflicting trials: the first number refers to position-conflicting trials and the second to word-conflicting trials; P and $_p$ = position information; W and $_w$ = word information; $\bar{x}$ is the grand mean; and ATT_i and AUT_i are the attentional and automatic effects, respectively, for dimension i.

The effect of attentional weight on word identity is

$$\begin{aligned} ATT_w &= \big[(10) + (12) + (13) + (15) - (9) - (11) - (14) - (16)\big] \cdot 8^{-1} \\ &= 5.73. \end{aligned}$$

and the effect of automatic weight on word identity is

$$\begin{aligned} AUT_w &= \big[(2) + (4) + (6) + (8) + (10) + (12) + (14) + (16) \\ &\quad - (1) - (3) - (5) - (7) - (9) - (11) - (13) - (15)\big] \cdot 16^{-1} \\ &= 13.09. \end{aligned}$$

These effects were added and subtracted from the grand mean according to the scheme in Table 5 to predict mean reaction time in each condition of Experiment 2. The predicted and observed values are presented in Table 2. Again, the predicted deviations from the grand mean were used to construct a linear contrast to test the fit of the model.

The attentional effects estimated in this way can be used to test the assumption made in this article and elsewhere (Logan & Zbrodoff, 1979) that the magnitude of attentional weights is proportional to cue validity and nothing else. From Eq. (5), the effect of attention to position information is $\alpha \cdot ATT_p \cdot t_p$ and the effect of attention to word identity is $\alpha \cdot ATT_w \cdot t_w$. Since cue validity was the same for position and word information,

ATT_p should equal ATT_w. Thus, the ratio of the attentional effects of position and word information should equal the ratio of the times that position and word information are available to influence the decision about relative position, that is

$$\frac{\alpha \cdot ATT_p \cdot t_p}{\alpha \cdot ATT_w \cdot t_w} = \frac{t_p}{t_w}$$

since

$$ATT_p = ATT_w.$$

This ratio can also be estimated from the difference in reaction time to relative position and to absolute position and word identity from the experiment reported in Appendix 1, that is,

$$\frac{RT_R - RT_p}{RT_R - RT_w} = \frac{t_p}{t_w}.$$

The hypothesis that attentional weights are affected primarily by cue validity (i.e., that $ATT_p = ATT_w$) can be tested by comparing estimates of t_p/t_w from Experiments 1 and 2 with the estimate from the experiment reported in Appendix 1.[5] The value from Experiment 1 was 3.21 and the value from Experiment 2 was 4.31, both of which are relatively close to the value 3.97 from the wide spacing condition of the experiment reported in Appendix 1. Thus, the data provide some support for the assumption that the magnitude of attentional weights is mostly proportional to cue validity. Clearly, this analysis requires replication and extension to situations in which the times t_p and t_w vary between conditions. Nevertheless, the agreement in the present experiments is promising.

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[5] Note that the same analysis cannot be performed with automatic effects since automatic weights reflect associative strength, among other things, and may not be equal for position and word identity.

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