JOURNAL OF VERBAL LEARNING AND VERBAL BEHAVIOR **15**, 587–605 (1976)

Long-Term Memory Search: An Intersecting Activation Process

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Subjects memorized subject–verb–object propositions and then judged whether verb–object probes appeared in the same proposition. Propositions either were connected via a common subject or were unconnected. Number of propositions associated with particular verbs and objects (fan) was also manipulated. Judgments were made under accuracy or speed emphasis. Reaction times and error rates were directly related to fan. Connectedness significantly increased reaction times and error rates for negative judgments. The data are consistent with a model which assumes that activation spreads from probe concepts in parallel through the propositional network, at a rate which varies inversely with the number of paths it must follow. When two sources of activation intersect, a positive response is generated. If no intersection is detected within some period of time, a negative response is initiated. A guessing model for errors was shown to account satisfactorily for all relationships between reaction times and errors in the data, including speed–accuracy trade-off effects, while assuming that memory search processes remain constant.

This paper is concerned with the process of searching long-term memory. We assume, in keeping with a number of current models of long-term memory (Anderson & Bower, 1973; Collins & Quillian, 1972; Norman, Rumelhart, & the LNR Research Group, 1975), that information in long-term memory is represented by a network of propositions interconnecting concepts. Within this network framework there have been a number of attempts to study the nature of the search processes that retrieve information from long-term memory (Anderson, 1974, 1975; Mohs, Westcourt, & Atkinson, 1975; Thorndyke & Bower, 1974). For instance, Anderson (1974) had subjects study sentences like *A hippie is in the park*. The number of sentences learned about a concept is referred to as the propositional fan for that concept, because each sentence would create an additional arc, pointing to a proposition, fanning out of the concept node in memory. In a reaction-time test, subjects were presented with probe sentences like *A hippie is in the park* and they verified whether or not they studied this sentence. In all of the above studies, it was found that reaction time increased with propositional fan.

The model proposed in these studies (HAM by Anderson & Bower, 1973) for the effect of propositional fan assumes that there is a serial search out of the concept nodes in memory. This search inspects the various propositions associated with a concept to see

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This research was supported in part by NSF Grant No. GB-40298 to J. Anderson and in part by the Office of the Advanced Research Projects Agency, under Order No. 1949, and was monitored by the Air Force Office of Scientific Research under Contract No. F 44620-72-C-0019 to the Human Performance Center. Requests for reprints should be sent to David King, who is now at the Department of Psychology, Marygrove College, Detroit, Michigan 48221.

if one encodes the same proposition as the test sentence. The time to discover the correct proposition or to reject all of the studied propositions will increase with fan. More recently, Anderson (1976) has proposed that all propositions from a concept are searched in parallel. However, he proposes a limited capacity parallel search in which the speed with which one proposition is searched is affected by the number of other propositions to be searched. This new model is called ACT.

Collins and Quillian (1972) also conceived of a parallel-search process. They proposed that activation spreads from a number of concepts in parallel along paths in the memory network. Paths of activation originating from different concepts may intersect. When they do, a central processor evaluates the nature of the path between the two concepts that led to the intersection to determine if it satisfies the relationship specified by the sentence. In a typical task, the subject might be asked to verify the sentence *A canary is an animal*. It was proposed that activation would spread from *canary* and *animal* until a point of intersection was found. The path along which the two activations intersected would be examined to see if it implied a *true* response to the test sentence.

One of the interesting phenomena which must be explained by these models has to do with false or negative responses to sentences containing concepts which are semantically related. Subjects are slower to respond to false sentences, such as *Some chairs are tables*, in which the subject and predicate concepts are related, than to sentences such as *Some chairs are feet*, in which the concepts have no obvious relation. This effect has been replicated using a number of different tasks requiring retrieval of real-world knowledge from long-term memory (Collins & Loftus, 1975; Collins & Quillian, 1972; Glass, Holyoak, & O'Dell, 1974; Meyer, 1970; Schaeffer & Wallace, 1970; Smith, Shoben, & Rips, 1974). A number of explanations of this phenomenon have been proposed, several of which do not use network models. However, the one we will consider here is that semantically related concepts are connected by paths in the memory network, and that extra time must be taken to check and reject these spurious paths in deciding that the sentence is false. This idea is closely related to one of the models for negative responses proposed by Collins and Quillian (1972).

One purpose of this paper is to coordinate the conceptions of long-term memory search arising from the HAM model and from the Collins and Quillian model. It is unclear whether or not the Collins and Quillian model as originally formulated can accommodate the effect of propositional fan. Anderson and Bower (1973) asserted that it could not, because it proposed that activation spread from a node in an unlimited capacity parallel fashion. That is, the speed of activation along one path was independent of the number of competing paths. More recently, Collins and Loftus (1975) have denied this, asserting that the original Quillian (1968, 1969) model was not committed on the issue of limited versus unlimited capacity search. However, to predict that the time to verify a sentence such as *A canary is an animal* will be linearly related to the distance between its concepts in semantic memory, as Collins and Quillian (1969) did, one must assume unlimited capacity. A limited capacity parallel model would predict that increasing semantic distance would result in exponentially increasing verification time. Whatever the original Quillian model, it certainly can be reformulated to have a limited capacity parallel search. This would change the predictions for the Collins and Quillian (1969) experiment, but would predict the effects of propositional fan.

The HAM model of Anderson and Bower (1973) does not expect intersections to occur of the variety proposed by Collins and Quillian. It does propose that searches can proceed in parallel from a number of concepts, but these searches are independent and do not intersect.

That is, in verifying *A canary is an animal*, a search process will have to progress all the way from *canary* to *animal* or vice-versa. There can be no "meeting in the middle."

One feature of previous research which has shown the effects of spurious connections between concepts is that experimental materials for these studies have been constructed from natural, "real-world" information. A potential deficiency of this approach is that, since the structure of the information in subjects' memories is not under the control of the experimenter, evidence concerning processes operating on those structures is fundamentally correlational and open to different interpretations according to one's assumptions about the memory structures. In the present study, the structure of the memorized information was controlled by using materials consisting of artificial facts, such as those used by Anderson and his colleagues (Anderson, 1974; Anderson & Bower, 1973; Thorndyke & Bower, 1974). In a critical test of HAM's selective, serial search assumption against the nonselective, parallel search assumption of the Collins and Quillian model, spurious connections were created among concepts in different propositions in the memory structure. Concomitantly, propositional fan was manipulated to provide evidence on the question of limited versus unlimited capacity.

In the experiment, subjects studied materials such as the following.

(1) *The hippie bored the minister.*
(2) *The hippie tripped the waitress.*
(3) *The lawyer kicked the fireman.*
(4) *The sailor amused the farmer.*

Figure 1 provides a simplified illustration of the propositional representation for these sentences according to either HAM or ACT, collapsing over nonessential nodes and links. The subject's task was to verify whether or not a verb and an object occurred in the same study sentence. Below are illustrated some possible probes:

(5) BORED MINISTER
(6) AMUSED FARMER
(7) BORED WAITRESS
(8) AMUSED FIREMAN

Probes (5) and (6) are positive, whereas probes (7) and (8) are negative. Note in Figure 1 that there is a spurious connection between *bored* and *waitress* in probe (7). This is because sentences (1) and (2) share a common subject. There is not such a connection in the case of probe (8). Thus, if the memory-searching process is sensitive to intersections among searches proceeding from different concepts, as Collins and Quillian propose, subjects may be slower to reject probes like (7) than probes like (8).

Probes (5)–(8) illustrate some of the basic conditions of the experiment. Probes like (7) are referred to as *negative connected* and probes like (8) are referred to as *negative unconnected*. As with negative probes, positive probes could come from sentences that either were connected to another sentence via the subject or were unconnected; however, there is no reason to expect any difference in how these two types of positive probes are processed. Orthogonal to the positive–negative and connected–unconnected dimensions, we manipulated the number of study propositions—one, two, or three—in which verbs and objects in the probe appeared. Thus, we would observe how the variable of propositional fan interacted with that of connectedness.

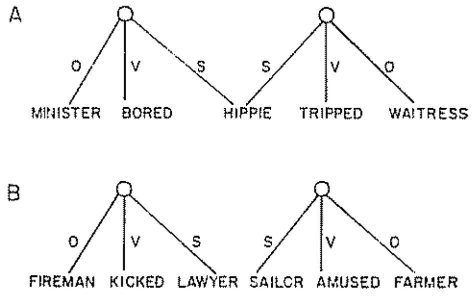

FIG. 1. A simplified network representation of the sentences in (A) the connected condition and in (B) the unconnected condition.

The final major manipulation in this experiment was the relative stress on speed versus accuracy in making these judgments. Careful consideration of the implications of the speed–accuracy trade-off is long overdue in the memory literature. Pachella (1974) has shown that theoretical interpretations of reaction-time effects are often invalid because they do not address accompanying changes in accuracy. It is particularly important in this experiment that we address ourselves to this question, since, on the basis of previous research, we could expect both propositional fan and connectedness to affect both speed and accuracy of responding. As Pachella points out, the only satisfactory solution to potential confounding of speed and accuracy effects is to develop a model for how errors are made in the process under investigation. Our attempt to manipulate error rates by relative emphasis on speed or accuracy, in conjunction with the other variables, was intended to provide a sound empirical basis for inferences about the production of errors during searches of memory.

METHOD

Subjects

Subjects were 14 females and 10 males recruited from the Human Performance Center subject pool at the University of Michigan. They were paid 2 dollars/hr for their participation (the experiment lasted from 2.5 to 3 hr), plus a bonus based on their performance.

Materials and Design

Each subject memorized a set of 40 sentences of the form *The subject verbed the object*, where both subjects and objects were definite descriptions of people, as in *The hippie bored the minister*. Different sets of 36 sentences were constructed for each subject, from the prototype array of 36 sentences shown in Table 1. Each subject also learned four other sentences like those in the (1, 1) cell, from which practice trials were generated.

TABLE 1

SCHEMATIC STRUCTURE OF SENTENCES

Number of sentences per verb	Number of sentences per object		
	1	2	3
1	$S_1V_1O_1$	$S_{10}V_5O_{13}$	$S_{19}V_9O_{19}$
	$S_1V_2O_2$	$S_{10}V_6O_{17}$	$S_{19}V_{10}O_{20}$
	$S_2V_3O_3$	$S_{11}V_7O_{16}$	$S_{20}V_{11}O_{22}$
	$S_3V_4O_4$	$S_{12}V_8O_{15}$	$S_{21}V_{12}O_{19}$
2	$S_4V_{13}O_5$	$S_{13}V_{18}O_{14}$	$S_{22}V_{17}O_{19}$
	$S_4V_{14}O_6$	$S_{13}V_{13}O_{15}$	$S_{22}V_{15}O_{21}$
	$S_5V_{15}O_7$	$S_{14}V_{16}O_{17}$	$S_{23}V_{16}O_{22}$
	$S_6V_{18}O_8$	$S_{15}V_{17}O_{14}$	$S_{24}V_{14}O_{21}$
3	$S_7V_{19}O_9$	$S_{16}V_{22}O_{18}$	$S_{25}V_{22}O_{20}$
	$S_7V_{21}O_{10}$	$S_{16}V_{19}O_{16}$	$S_{25}V_{20}O_{22}$
	$S_8V_{22}O_{11}$	$S_{17}V_{20}O_{18}$	$S_{26}V_{21}O_{21}$
	$S_9V_{20}O_{12}$	$S_{18}V_{21}O_{13}$	$S_{27}V_{19}O_{20}$

In Table 1, the strings of symbols indicate different sentences. Thus, the symbol $S_1V_2O_2$ denotes a sentence composed of the first subject, second verb, and second object. Individual verbs appeared in one, two, or three sentences in the set, as did individual objects, thus manipulating verb fan and object fan, respectively. Within each cell in Table 1 (i.e., each combination of verb fan and object fan), there are four sentences; the upper two of these share a common subject and are hence *connected* sentences; the lower two have different subjects and are thus *unconnected* sentences. Different sentence sets were created by randomly rearranging the list of 27 subjects, 22 objects, and 22 verbs to fill roles in the prototype sentences in Table 1.

The data-collection phase consisted of four blocks of 200 trials each. On each trial, the subject made a co-occurrence judgment about a pair of words from the sentences. Judgments about verb–object pairs provided the experimental data. Positive probes contained a verb and an object from the same sentence; negative probes were constructed by pairing each verb with an object from the other sentence in the same half of the cell in Table 1. Each of the 36 positive and 36 negative probes was presented once with the verb preceding the object and once with the object preceding the verb. Thus, each block contained 144 experimental trials. Each block also contained 36 filler trials, consisting of subject–verb probes, likewise counterbalanced for response and presentation order. These were included to force the subject to keep all of the memorized material current in his memory and to discourage his choosing idiosyncratic search strategies based only on searching verbs and objects. Each block began with 20 trials of verb–object and subject–verb probes selected from the four practice study sentences. Data from these probes were not analyzed; they were included to allow the subject to adjust to the payoff system for each block and to allow for the dissipation of warm-up effects. The order of these trials, as well as the order of the remaining 180 trials of each block, were randomized.

Two of the four blocks were run under accuracy emphasis and two were run under speed emphasis. Order effects for this variable were controlled by having the accuracy blocks occur first and last for half the subjects and second and third for the other half. The overall design was a completely within-subjects factorial design involving the factors of response (positive versus negative), presentation order (verb first or object first), verb fan, object fan, connectedness, and speed versus accuracy emphasis. There were 144 conditions defined by factorial combination of all of these variables. Each subject provided four observations to each condition, for a total of 96 observations per condition.

Procedure

Subjects sat in booths containing a TV screen, a keyboard, and two push buttons, all of which were connected to an IBM 1800 computer. The session was divided into a study phase, a test phase, and a reaction-time phase.

In the study phase, the 40 sentences were displayed one at a time on the screen. Subjects were instructed that "this experiment is concerned with the nature of structural representations of sentences in memory" and were told to "compose a continuation of each sentence which you feel is consistent with its meaning" and write the entire sentence and its continuation on a sheet provided. By pushing a button, the subject initiated the display of the next sentence. After he had written continuations to all 40 sentences, his continuation sheet was removed and the test phase began. During the test phase, two of the words from a sentence would appear on the screen, and the subject was required to type the third word from the sentence on the keyboard, whereupon the computer would tell him whether he was right or wrong, and display another pair. All 120 possible pairs of words from the 40 three-word sentences were tested using a dropout procedure. If a pair was answered correctly, it dropped out of the list; if an error was made, the pair reappeared later in the sequence. The test phase terminated when the subject had responded correctly to every pair in the list. The sequence of both study trials and test trials was randomized separately for each subject.

In the reaction-time phase, each block began with instructions concerning the payoff system for that block. On accuracy trials, subjects earned 40 points for a correct answer, minus one point for each 0.1 sec of reaction time; an error resulted in a penalty of 120 points. During the speed blocks, subjects earned 40 points for each correct response, minus two points for each 0.1 sec of reaction time, and were penalized 35 points for each error. Points were converted into bonus money at the end of the experiment at the rate of 75 points to 1 cent. Subjects typically earned 9,000 to 13,000 points during the experiment.

Each reaction-time trial consisted of the following sequence of events. First, a warning signal appeared in the center of the screen. It remained visible for 0.5 sec and disappeared. Following a 0.3-sec blank interval, the first word appeared in a position immediately above where the warning signal had been. There was a 0.5-sec delay, and then another word appeared two lines below the first word. The subject responded by pushing the Yes or No button, according to whether or not the words had occurred in the same study sentence. The words then disappeared and a feedback message appeared, informing him of his correctness, his reaction time in tenths of a second, how many points he earned on that trial, and the total number of points he had earned. Reaction time was measured to the nearest millisecond from the time of the onset of the second word to the time of the button press. Yes and No buttons were assigned to the preferred and nonpreferred hand, respectively.

RESULTS AND DISCUSSION

Correct reaction times and error rates were averaged for each subject in each condition, and the resulting means were subjected to a within-subjects analysis of variance in which the significance of each experimental effect was assessed by using the appropriate treatment-by-subjects interaction as the error term. Since materials varied with subjects, materials effects are included in the treatment-by-subjects interactions; thus, generalizing across subjects does not involve the language-as-fixed-effect fallacy (Clark, 1973). Separate analyses were performed on the accuracy and speed emphasis data because variances were different under these two conditions. Results of these analyses are summarized in Table 2. For the sake of brevity (there were 31 main effects and interactions in each analysis), only those effects for which at least one of the four analyses of variance yielded a significant F ratio are reported.

As Table 2 illustrates, there were highly significant effects of response type, verb fan, and object fan. Table 3 presents the data classified by these three variables collapsing over the variables of presentation order, connectedness, and speed stress. Table 3 shows that reaction time is greater for negative responses and increases as a function of

TABLE 2

SIGNIFICANT F RATIOS IN ANALYSES OF VARIANCE

		Accuracy emphasis		Speed emphasis	
Source	df	Reaction-time data	Error data	Reaction-time data	Error data
Response (R)	1, 23	42.44***	.118	99.02***	3.782
Presentation order (P)	1, 23	3.170	2.745	.726	5.471*
Verb fan (V)	2, 46	16.21***	14.39***	41.17***	24.50***
Object fan (O)	2, 46	9.606***	14.13***	14.81***	7.228**
Connectedness (C)	1, 23	11.10**	8.903**	8.117**	10.16**
R × P	1, 23	.906	.554	5.676*	1.065
R × V	2, 46	1.859	12.59***	.163	29.924***
R × O	2, 46	.912	5.757**	2.542	3.785*
R × C	2, 46	26.83***	23.45***	11.86***	12.54***
P × V	2, 46	6.696**	.818	4.536*	.862
V × C	2, 46	.652	.119	3.342*	.354
P × V × O	4, 92	.562	.394	2.925*	.504

* $p < .05$. ** $p < .01$. *** $p < .001$.

TABLE 3

Reaction Times (Milliseconds) and Error Rates (in Parentheses) for Positive and Negative Responses as a Function of Verb Fan and Object Fan

Verb fan	Positive Object fan 1	Positive Object fan 2	Positive Object fan 3	Negative Object fan 1	Negative Object fan 2	Negative Object fan 3
1	786	853	852	998	1001	1070
	(.073)	(.067)	(.064)	(.161)	(.127)	(.178)
2	830	947	997	1014	1090	1115
	(.080)	(.198)	(.177)	(.124)	(.125)	(.135)
3	926	1042	1038	1121	1171	1200
	(.107)	(.242)	(.220)	(.146)	(.181)	(.240)

verb fan and object fan. These results are consistent with others reported in studies that have looked at the effects of propositional fan (Anderson, 1974, 1975; Mohs et al., 1975; Thorndyke & Bower, 1974).

The major concern of this experiment is the effect of connectedness on negative responses. Connectedness was significant both as a main effect and in interaction with response, but inspection of Table 4 shows that the main effect is entirely due to the effect of connectedness on negative responses. As might have been predicted from past research with natural materials, spurious connections increased both error rate and reaction time for negatives.

Figures 2 and 3 show the effect of connectedness on correct negative reaction times and error rates, respectively, as a function of total fan from both words in the pair. Low fan pairs were those for which total fan from both words was two or three; that is, pairs in the (1, 1), (2, 1), and (1, 2) conditions of Table 1. Medium fan pairs had a total fan of four; they were pairs from the (2, 2), (1, 3), and (3, 1) conditions of Table 1. High fan pairs had a total fan of five or six, being those from the (2, 3), (3, 2), and (3, 3) conditions. There is an interaction between fan and connectedness for negative judgments such that the connectedness effect is less at higher fan. We constructed contrasts to see if the interactions apparent in Figures 2 and 3 were significant. The interaction between overall fan and connectedness is significant in each panel of Figure 2: In the accuracy condition, $F(1, 92)$

TABLE 4

Effect of Connectedness on Reaction Times and Error Rates for Positive and Negative Responses

Response	Accuracy emphasis Connected	Accuracy emphasis Unconnected	Speed emphasis Connected	Speed emphasis Unconnected
Yes	1009	1010	833	835
	(.110)	(.128)	(.150)	(.156)
No	1254	1134	1017	941
	(.161)	(.086)	(.233)	(.144)

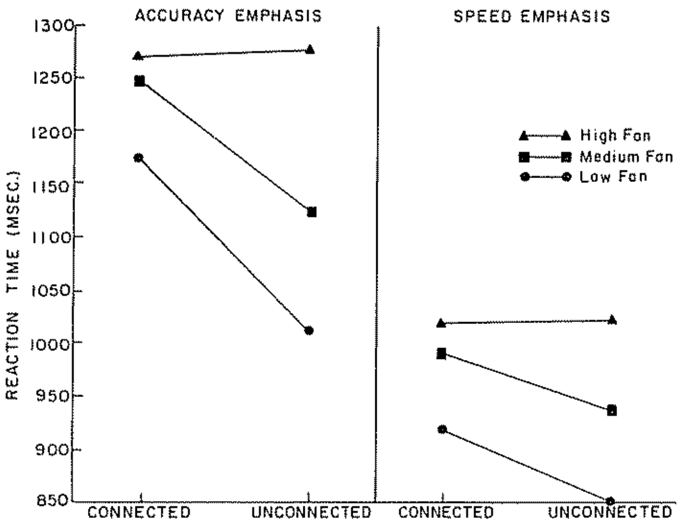

FIG. 2. Effect of connectedness and fan on reaction times for correct negative responses.

$= 3.983$, $p < .05$, and in the speed condition, $F(1, 92) = 9.379$, $p < .01$. In Figure 3, the interaction is significant in the speed condition, $F(1, 92) = 5.867$, $p < .05$, but not in the accuracy condition, $F(1, 92) = 2.034$, although it is in the same direction.

Interpretation of Principal Effects

The model to be proposed to account for this pattern of data can be seen as a merging of assumptions from the Quillian intersection model and from the HAM model, with some additional assumptions to account for relations between speed and accuracy. The model can also be seen as an elaboration of the ACT model for fact retrieval (Anderson, 1976). In actual fact, results from this experiment were one of the factors that led to the formulation of the ACT model.

The model assumes that, when a probe is

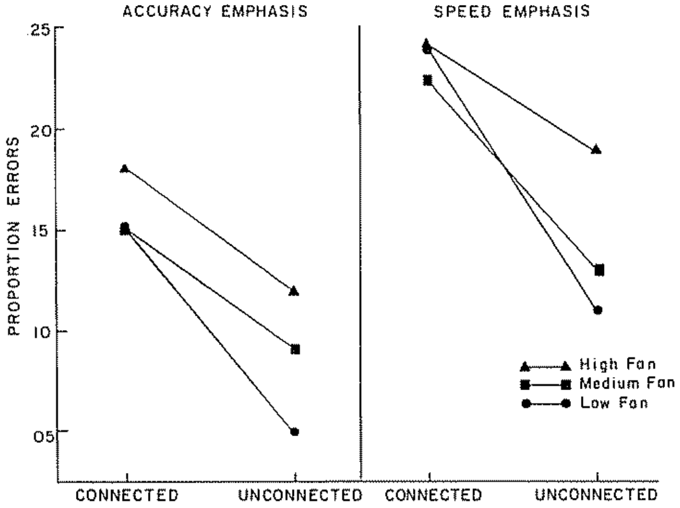

FIG. 3. Effect of connectedness and fan on error rates for negative responses.

presented, activation spreads in parallel along all paths from each concept in the probe. A subject responds "yes" if there is an intersection of activation among the concepts and if the path of intersection corresponds to the network structure being sought. The model assumes that subjects will respond "no" if a certain period of time passes after the encoding of the probe without an intersection being discovered. This hypothesis has been dubbed the *waiting model* for negative responses (Anderson, 1976).

The model assumes that propositional fan has its effect on positive responses by slowing the rate at which the activation spreads through memory. We will further assume that the waiting process is adjusted for the propositional fan of the negative probes; that is, that the process will wait longer for probes of higher propositional fan. This is a sensible strategy, since intersections would take longer to occur if these probes were positive. Specifically, we propose that the negation process waits as long as it would take to obtain an intersection for a probe of that fan, plus an additional time that does not change with fan. These assumptions would account for the fact that the effect of fan is approximately the same for positive and negative responses and that negative responses take consistently longer than positive responses at all levels of fan.

The effect of connectedness on negative reaction times indicates that activation proceeding from a concept can cross propositional boundaries and intersect with activation proceeding from another concept. This spurious path of intersection must be checked, increasing the reaction times for correct judgment of these probes. However, the interaction of connectedness and fan indicates that such spurious paths of intersection are not always discovered, particularly at high levels of fan. This fact is informative, because it suggests that the propositions associated with the probe concepts are not searched exhaustively, as the HAM model assumed. The effect is compatible with the waiting model, since at higher levels of fan the spurious path would take much longer to become activated and the waiting time would be more likely to expire before an intersection were discovered.

The fact that connectedness affects both response times and error rates suggests that, at least some of the time, intersections between connected propositions are not checked, but rather produce false positive responses. However, it is possible that the effect of connectedness on error rates is only a secondary consequence of a more basic effect of increasing response times. This fact would be predicted by any model of error production which assumed that the longer a stimulus-controlled process takes to generate a response, the greater the likelihood that an error will occur. In this case, since subjects took longer to respond to connected negative probes, they had more of an opportunity to make errors.

This hypothesis is disconfirmed by the data in Figure 4, which presents a speed–accuracy plot of the negative data. Each point represents the data from one of the nine fanning conditions crossed with the connectedness factor, collapsing across order of presentation and speed stress. Each point is placed in Figure 4 according to its error rate and its reaction time. According to the assumption that errors increase as a function of increasing processing time, errors should increase monotonically with reaction time in both the connected and unconnected conditions. In fact, the relationship is roughly monotonic for the unconnected conditions, but distinctly nonmonotonic for the connected conditions. The critical feature of this graph lies in comparison of error rates for conditions which produced comparable reaction times. There are several connected conditions for which error rates are substantially higher than unconnected conditions having roughly comparable reaction times. This means that connectedness has an effect on error rate that is independent of its effect

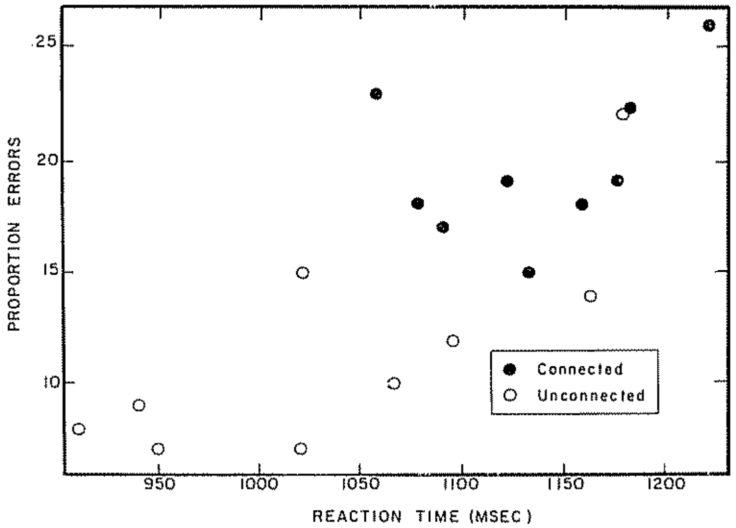

FIG. 4. Speed versus accuracy of connected and unconnected negative responses.

on reaction time. Thus, intersections in the activation process sometimes appear to cause subjects to initiate a positive response.

Head-Start Effects

Another question which can be asked of the data is what is the effect of allowing a 0.5-sec head start on the search process from the first probe word? The HAM model predicts that the fan of the first word should have a larger effect on overall reaction time than the fan of the second word in this task. This prediction follows from the assumption that reaction time is determined by the fastest of a number of racing search processes. If one process is given a head start, then it will tend to be the first to reach completion. Since its duration will depend on the number of propositions which it has to search, reaction time will tend to depend more heavily on the fan of the word presented first. This prediction was tested by Anderson (1974), who precued the subject by saying aloud the name of either a person or a location about 1 sec before visually presenting a probe sentence of the form *A person is in the location*, for the subject to verify. A marginally significant trend ($p < .10$) in the direction predicted by the HAM model was observed; fan of the precued word had a 40-msec larger effect than fan of the uncued word.

In the present study, we find a large effect of head start in the opposite direction. The relevant data are summarized in Table 5, which presents mean reaction times for all probes except those in the 1–1, 2–2, and 3–3 fanning conditions, combining over different response types and fanning levels. High–low probes are those for which the fan of the word presented first exceeds the fan of the word presented second; that is, 2–1, 3–1, and 3–2 probes. Low–high probes are the same ones presented in reverse order. Table 5 shows that reaction times to a probe are greater if the higher-fan word is presented second.

TABLE 5

EFFECT OF FIRST- AND SECOND-WORD FAN ON REACTION TIMES UNDER ACCURACY AND SPEED EMPHASIS

	Fan combination	
Emphasis	High–Low	Low–High
Accuracy	1053	1130
Speed	883	926

This is true for both positive and negative probes, in each fanning condition. Contrasts constructed to test for significance of this effect are highly significant: $F(1, 92) = 17.41$, $p < .001$ for accuracy emphasis and $F(1, 92) = 15.33$, $p < .001$ for speed emphasis.

Although this result is contrary to the prediction of the HAM model, it is not incompatible with the parallel-activation model we are proposing. In the case of positive probes, consider the fact that if activation from the concept presented first begins to spread before activation from the second concept, it will have travelled relatively farther through the network than the activation from the second concept. Now, at every intermediate node in the network, activation must be subdivided, reducing its rate of spread in proportion to the number of paths leading out from that node. (According to ACT, there are many intermediate nodes, even within a single proposition.) Thus, the activation spreading from the concept given a head start is likely to be travelling relatively more slowly than the activation from the second concept by the time that they intersect. Hence, the total time to complete the search, which is going to be affected most by the speed of the faster search process, will depend more on the fan of the second word than the first word.

The discrepancy between the strong effect of head start in this study and the weak effect in the opposite direction obtained by Anderson (1974) may be due to procedural differences between the two studies. Anderson precued his subjects verbally by saying one word aloud prior to presenting a sentence visually. While this manipulation had a large (254 msec) and highly significant effect on overall verification times as compared with a control condition in which subjects were precued with "none," it had an almost negligible effect on search rates from cued versus noncued words. This suggests that the locus of the effect of the precuing manipulation was in the encoding process, rather than in the search process. In fact, since the interaction of fanning and cueing did not reach conventional levels of statistical significance, one should probably not reject the hypothesis that the true effect of precueing on the search process was zero. In contrast, the head-start manipulation of the present study clearly did affect search rates, in a manner which favors the intersecting activation model over the HAM model.

There is another word-specific fanning effect in the data for which we have no explanation. In comparing the effects of verb fan and object fan on reaction times, the effect of verb fan proved to be significantly larger than the effect of object fan. The test for this effect yielded an F of 4.66 in the accuracy condition and an F of 5.21 in the speed condition, both $ps < .05$. This effect is anomalous in the context of other studies using similar materials in which no such differential effects on search rates due to word class were found. (Anderson, 1974, 1976; Thorndyke & Bower, 1974).

Speed–Accuracy Trade-off Effects

The facts regarding the relationship between speed and accuracy in the experiment are these: (1) Correct reaction times were 195 msec faster and error rates were 5% greater under speed emphasis than under accuracy emphasis, both of which are highly significant differences. (2) Virtually all of the experimental effects obtained in the data, either on reaction times or errors, were qualitatively the same under accuracy emphasis and speed emphasis. (3) The absolute magnitude of the experimental effects under speed emphasis seemed somewhat reduced in the case of reaction times, and perhaps magnified in the case of error rates.

These facts can be accounted for by an extension of the model offered by Mohs et al. (1975) for the relationship between errors and reaction times in their experiment, which used a similar memory-search task. Their model assumed that the subject has a certain tendency to make guesses, which can produce errors. These guesses can be assigned a probability distribution as a function of time. An error will occur when an incorrect guess is made before the stimulus-controlled process has generated a correct response. In effect, there is a race between the stimulus-controlled process and the guessing process to determine the response.

Within the context of this model, it can be assumed that subjects trade accuracy for speed by speeding up their distribution of guessing times, thereby producing more errors, but also decreasing their average correct reaction time. It should be appreciated that the mean time for stimulus-controlled responses, as well as guesses, will decrease with a decrease in the distribution of guessing times, because long stimulus-controlled responses will be beaten out by guesses. Besides decreasing reaction time and increasing error rate, speeding up guesses will decrease reaction-time differences among conditions and increase error rate differences, as observed under speed emphasis in the present experiment.

Fit of a Quantitative Model

We developed a quantitative model to embody the assumptions of the theory and fit this model to the data. This model-fitting enterprise was undertaken to perform two related functions. First, it serves as a rigorous test of whether or not our theoretical assumptions account satisfactorily for the complex pattern of data in this experiment. Second, it provides a stringent test of the Mohs et al. (1975) error model, by determining whether or not it can account for the speed–accuracy trade-off effects found in the present data. We hoped to find that our model could be fitted satisfactorily to the data with the same memory-search parameters under speed emphasis as under accuracy emphasis, estimating different values only for the parameters of nonmemory processes, such as the distribution of guesses. This would constitute strong support both for the accuracy of our theory about the basic memory processes and for the Mohs et al. model of the relation between reaction time and errors. What follows is largely a verbal description of the model and its parameters. In order to avoid burdening the reader with mathematical apparatus, the equations have been placed in the Appendix.

When the subject is presented with the first probe word, he is assumed to encode that word and activate its node in long-term memory. Similarly, when the second probe word is presented, its node will be activated in the long-term memory network. Because the first probe word is presented 0.5 sec ahead of the second word, it is assumed that activation begins to spread from the former before it begins to spread from the latter. The activation process is assumed to generate responses to different kinds of probes as follows. If the probe is positive, the subject will respond "yes" when activation from the two nodes intersects. If the probe is an unconnected negative, he will respond "no" after waiting for some period of time without an intersection occurring. If the probe is a connected negative, he will either (1) respond "no" if an intersection is not detected, (2) respond "no" after detecting an intersection, checking it, and finding it to be spurious, or (3) respond "yes" after detecting a spurious intersection and failing to check it. Errors, except for some false positives to connected negative probes, are assumed to be produced by a guessing process.

The processing of a positive probe is depicted in Figure 5. There we have illustrated schematically a proposition P interconnecting a subject S, a verb V, and an object O. In (A), V is presented first and is activated in memory. In (B), activation has begun to spread from V towards the proposition node P. In (C), O is presented and activated in memory. Activation from V is portrayed as having reached P by this point. In (D), activation from P has spread outward toward S and O and has intersected with activation proceeding from O. A similar picture could be created for the case when O was presented first and V was presented second.

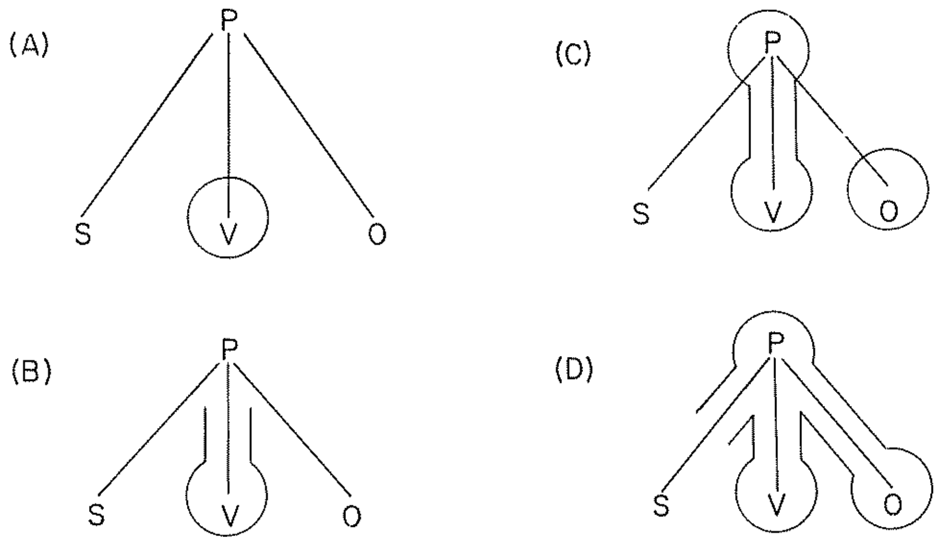

FIG. 5. Stages in the spread of activation between verb (V) and object (O) of a positive probe.

Reaction time is measured from the presentation of the second word. Therefore, a positive ("yes") reaction time will consist of components including the time to encode the second word, the time necessary to complete the activation of the path between V and O (producing an intersection), and the time necessary to execute the response. Of these, the encoding and response times are assumed to be constant for all probes and are subsumed in parameter K. However, the time to activate the propositional structure will vary as a function of the fan from V and O.

We will not distinguish between the fan of verbs and objects; however, we will distinguish between the fan of the first probe word and that of the second probe word. The number of propositions (fan) attached to the first word (V in Figure 5) and to the second word (O in Figure 5) will be referred to as n_1 and n_2, respectively. The model proposes that the time for activation to travel along a path is inversely proportional to the number of paths it must travel. It we let α denote the mean time to activate one link from a node with a fan of one, then the average rate at which activation proceeds from O to P will be $1/(n_2\alpha)$. To simplify the derivation of an expression for how long it will take for activation to travel from V until it intersects with the activation travelling from O, we will assume that activation from V has reached P by the time that O has been activated in memory, (C) of Figure 5. (This is a simplifying assumption; the predictions of the model would not be altered significantly if other assumptions about the head start of activation from V were adopted.) Since there are two paths leading out of P, the activation which originated at V will be slowed by a factor of two as it travels the link from P toward O. Thus, the mean rate at which this activation will spread from P to O will be $1/(2n_1\alpha)$. The time for the two activation processes to intersect will be a function of their respective rates.

Based on the notion of Mohs et al. (1975), it is assumed that a guessing process with an average completion time of γ races against the search process. If it happens to terminate before the search process has produced an intersection, the subject guesses "yes" with probability g and guesses "no" otherwise. Thus, on positive trials, response and reaction time are determined by the faster of two racing processes: the search process, which is assumed always to produce a correct response, and the guessing process, which produces an error with probability $1-g$.

Reaction times for unconnected negative responses are assumed to include the same encoding and response constant K and a waiting time that is equal to the activation time for that condition plus an additional time W. As with positive probes, the probability of error and the reaction time will be determined by whether the stimulus-controlled process or the guessing process finishes first.

The processing of a connected negative probe is illustrated in Figure 6, at a point comparable to that depicted in (C) of Figure 5. Again, the simplifying assumption is made that activation from V_1 has proceeded as far as P_1 by the time that activation begins to spread from O_2. Note that in this diagram activation has to traverse three links to get from P_1 to O_2, or vice-versa, and that activation will be subdivided as it passes out of P_2. The mean rate at which activation spreads from P_1 will be $1/(2n_1\alpha)$, while the mean rate at which activation travels from O_2 will be $1/(n_2\alpha)$ until it reaches P_2, after which it will spread at a rate of $1/(2n_2\alpha)$. The mean time for these two processes to intersect will be a function of their respective rates.

If an intersection is discovered, the subject is assumed to accept it without checking with probability a and immediately generate a false positive response. With probability $1-a$, he will check the intersecting path, taking extra time C, and make a correct negative response. It is also possible that the waiting time for negation will expire before the activation process has discovered the intersection, in which case the subject will correctly respond "no", or that the guessing process will expire before either of these, in which case the subject makes an error with probability g. The mean reaction time and the probability of an error are thus determined by the fastest of three simultaneous processes: the guessing process, the waiting process, and the spurious intersection process.

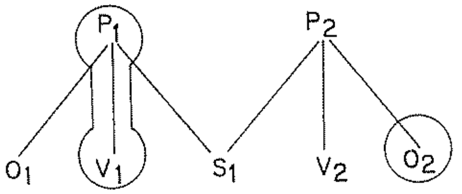

FIG. 6. State of activation for a connected negative probe when the second word (O_2) is presented.

The model thus has seven parameters; K, γ, W, α, g, a, and C. Initially, the model was fit to the speed and accuracy data separately, estimating different values for each parameter under speed and accuracy emphasis. The program STEPIT (Chandler, 1965) was used to find the 14 values that gave the best fit to the data, by minimizing the value of a chi-square statistic measuring the goodness of fit of the model to the observed times and error probabilities in the 72 conditions defined by factorial combination of n_1, n_2, connectedness, response, and speed–accuracy emphasis. With 144 data points being fit, and with 14 parameter values being estimated, this statistic has 130 degrees of freedom. The least chi-square value obtained by the model was 210.10, which indicates significant ($p < .001$) deviation between observed and predicted values. The model accounts for 95.1% of the variance in reaction times and for 74.0% of the variance in error rates. Given the general experience of model-fitting in mathematical psychology, this is quite good, especially considering that 144 data points were being fit.

One of our major concerns in developing the model was to see how well it could account for speed–accuracy trade-off effects if memory-search parameters were held constant. Accordingly, we fit the model to the data a second time, permitting just three of the seven parameters to vary between speed and accuracy conditions. We adopted the following assumptions regarding a subject's strategy in dealing with speed stress: (1) that under speed stress, the subject could save time (at the expense of raising his error rate) by guessing sooner, thus decreasing the guessing process time γ; (2) that under speed stress he could save time (again at the expense of making errors) by being more willing to respond "yes" without checking upon finding a spurious intersection, thus increasing the probability a of accepting a spurious intersection; and (3) that under speed stress he may be able to take up slack in the encoding and response generation processes measured by K, such as by pushing response buttons faster. We required the activation time parameter α, the intersection checking time parameter C, and the waiting time parameter W to remain constant, as these were hypothesized to reflect memory processes not under the strategic control of the subject. In addition, there seemed to be no good reason why his guessing tendency, as measured by g, should change between speed and accuracy emphasis, so this too was held constant. Under these constraints, only 10 values were estimated in fitting the more specialized version of the model to the data. These parameter values, as estimated by the STEPIT program, are given in Table 6. The chi-square measure of deviation with 134 degrees of freedom had a value of 214.38. To determine whether or not the constraints on memory-search parameters resulted in a significant reduction in the accuracy of the general model, the difference between the chi-square values for the two model-fits can be assessed. This difference, 4.28, is chi-square distributed with 4 degrees of freedom and is not significant. Therefore, our hypothesis concerning the invariance of memory search processes under speed versus accuracy task constraints is strongly supported.

The quality of the predictions of the model may be assessed by consulting Figures 7, 8, and 9, which present the model's predictions for positive, unconnected negative, and connected negative probes, respectively. In these figures, reaction time and probability error are plotted as a function of low, medium, and high fan. The most systematic point of misfit of the model concerns its underprediction of the effect of fan on error rates for positive probes. According to the model, errors only occurred because of guesses. However, it should be noted that the model includes no assumption about forgetting. If a subject should ever forget a sentence, he would presumably respond "no" to positive probes from that sentence, although he would still respond correctly to negative probes. Such forgetting would be more probable at high fan where verbs and objects appeared in several sentences each, creating interference for individual sentences in which they appeared. Thus, if any forgetting occurred during the course of the experiment, it would be likely to increase the number of errors to positive probes at high fan, which may explain the model's underprediction of this effect.

TABLE 6
PARAMETERS OF THE MODEL

Parameter	Emphasis: Accuracy	Emphasis: Speed
Encoding and response constant, K	647 msec	513 msec
Activation time (per link), α	370 msec	
Additional waiting time for negation, W	210 msec	
Guessing time, γ	1810 msec	1250 msec
Probability of guessing "yes", g	.383	
Probability of accepting a spurious intersection, a	.373	.580
Time to check a spurious intersection, C	1903 msec	

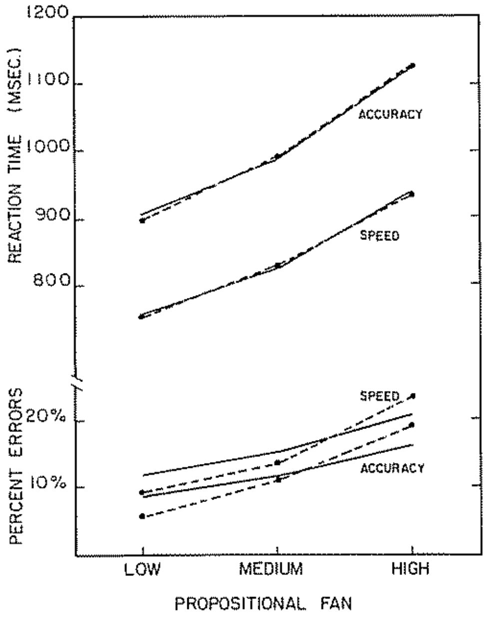

FIG. 7 Fit of the model for positive probes—dashed lines connect the observed values and solid lines connect the predicted values.

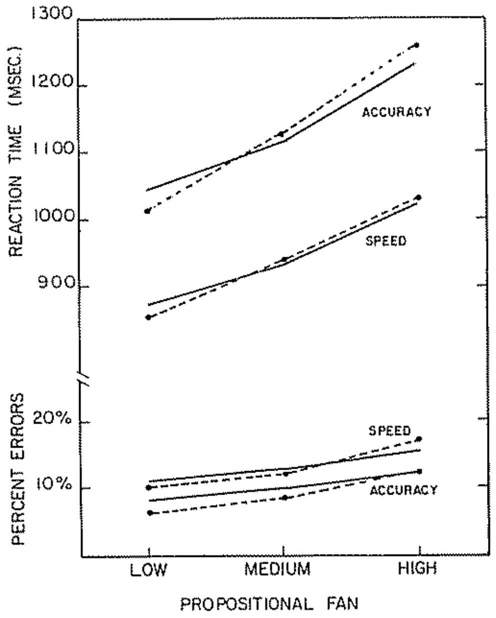

FIG. 8 Fit of the model for unconnected negative probes—dashed lines connect the observed values and solid lines connect the predicted values.

A few comments about the model may serve to put it in perspective. It should be noted that the parameter estimates depend to a certain extent on assumptions which are not central to the theory. For instance, the activation parameter α depends on the complexity of the propositional structures the subject is assumed to be searching; the structures depicted in Figures 5 and 6 have been deliberately simplified from their assumed representations according to ACT. A slightly different example is that the low value of *g* is probably a consequence of inducing subjects to make "yes" errors to connected negative probes and may also have been affected by forgetting, which would increase the number of "no" errors in the experiment. A third example is that the estimate of *W* may be exaggerated by the fact that all subjects answered "no" with their nonpreferred hand. However, it should be pointed out that similar studies in which hand assignment has

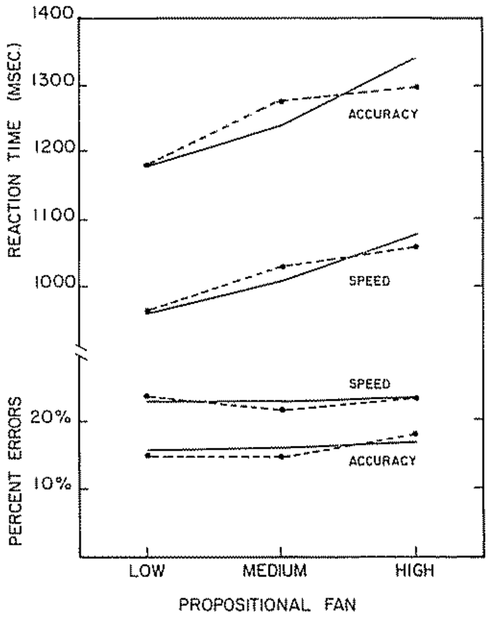

FIG. 9 Fit of the model for connected negative probes—dashed lines connect the observed values and solid lines connect the predicted values.

been counterbalanced have also found consistent differences between positive and negative response times, supporting the notion that extra time is involved in the process of negation.

More important than the parameters themselves are the theoretical processes they represent. The notion of a limited capacity parallel-activation process that is sensitive to intersections is central not only to the account of the present data, but also, we believe, to the process of searching long-term memory in other contexts as well. Certainly, one of the most significant features of the model is its relatively simple account of errors. The success of the Mohs et al. guessing model in accounting for the relationships between speed and accuracy in this experiment has reassuring implications for research in cognitive psychology, since it suggests that errors are made independently of stimulus information and that there are strategy-free components of memory-search processes that are unaffected by external task constraints such as speed stress.

APPENDIX

The equations of the model, and brief explanations of their derivation, are given below. For the sake of mathematical tractability, all processes are assumed to have exponentially distributed completion times.

In the situation depicted in Figure 5, the mean time for activations from P and O to intersect going from (C) to (D), is given by

$$A = \frac{2n_1 n_2 \alpha}{2n_1 + n_2}. \qquad (1)$$

The mean time for a correct "yes" response will be determined by the encoding and response constant K and by the time taken by the faster of the activation process and the guessing process. Thus,

$$T(Y) = K + \frac{1}{(1/A) + (1/\gamma)}. \qquad (2)$$

The additional time W is added to the activation time in determining how long the subject will wait before making a negative response. Thus, the mean time for a correct response to an unconnected negative is given by

$$T_u(N) = K + \frac{1}{(1/(A+W)) + (1/\gamma)}. \qquad (3)$$

The probability of an error is determined by which of the two racing processes finishes first. The following expression gives the probability that the guessing process finishes first and that the subject guesses "no", producing a false negative response to a positive probe.

$$P(\mathrm{FN}) = \frac{(1/\gamma)(1-g)}{(1/A) + (1/\gamma)}. \qquad (4)$$

Similarly, the probability of an error to an unconnected negative probe is given by

$$P_u(\mathrm{FP}) = \frac{(1/\gamma)g}{(1/(A+W)) + (1/\gamma)}. \qquad (5)$$

For connected negative probes, a third process races against the negation process and the guessing process: namely the process which discovers a spurious intersection. The time for the activation processes from P_1 and O_2 to intersect in Figure 6 is given by

$$S = \frac{5n_1 n_2 \alpha}{n_1 + n_2}. \qquad (6)$$

Two kinds of errors to connected negative probes are possible: namely, wrong guesses and the mistake of deciding (with probability a) to respond "yes" to a spurious intersection without checking it. The overall probability of an error is thus given by

$$P_c(\mathrm{FP}) = \frac{(1/\gamma)g}{(1/(A+W)) + (1/\gamma) + (1/S)} + \frac{(1/S)a}{(1/(A+W)) + (1/\gamma) + (1/S)}. \qquad (7)$$

The probability of the guessing process finishing first and producing a "no" response to a connected negative probe is given by

$$p_1 = \frac{(1/\gamma)(1-g)}{(1/(A+W)) + (1/\gamma) + (1/S)}. \quad (8)$$

The probability of the waiting process finishing first, and producing a correct negative response, is given by

$$p_2 = \frac{(1/(A+W))}{(1/(A+W)) + (1/\gamma) + (1/S)}. \quad (9)$$

The probability of the activation process finishing first, and the subject then deciding to check the spurious intersection, is given by

$$p_3 = \frac{(1/S)(1-a)}{(1/(A+W)) + (1/\gamma) + (1/S)}. \quad (10)$$

The mean time for any of these three processes to finish when all three are racing against each other is given by

$$t = \frac{1}{(1/(A+W)) + (1/\gamma) + (1/S)}. \quad (11)$$

The expected mean reaction time for a correct "no" response to a connected negative probe is therefore given by the following expression, where C refers to the time to check a spurious intersection.

$$T_c(\mathrm{N}) = K + \frac{p_1 \cdot t + p_2 \cdot t + p_3 \cdot (t + C)}{p_1 + p_2 + p_3}. \quad (12)$$

The statistic that was minimized by STEPIT in estimating the parameters of the model is

$$\chi^2 = \sum_{i=1}^{72} \left[\left(\frac{T_i - \bar{T}_i}{s} \right)^2 + \frac{(f_i - NP_i)^2}{NP_i} + \frac{(f_i' - N(1-P_i))^2}{N(1-P_i)} \right], \quad (13)$$

where i indexes the 72 (first-word fan × second-word fan × response × connectedness × speed emphasis) conditions, T_i is the predicted reaction time for condition i, T_i is the observed mean reaction time for condition i, s is the standard error of the observations (for speed or accuracy emphasis), f_i is the number of errors for condition i, f_i' is the number of correct responses for condition i, N is the number of observations in each condition (i.e., 192), and P_i is the predicted error probability for condition i.

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(Received July 26, 1976)