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ABSTRACT

It has been found that an information-processing analysis of latencies collected in an immediate sentence recall task using children with median age 4 years 4 months favors a serial processing mechanism. This mechanism consists of three major parts: (1) The detection of a clausal boundary, (2) the assessment of whether or not the observed noun-verb-noun structure satisfies a unique semantic constraint (in terms of the meaningfulness of interchanging its two clausal nouns), and (3) the assessment of whether the observed surface sequence satisfies a canonical order of subject-verb-object. (Author/DP)

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A LATENCY ANALYSIS OF STRATEGIES UNDERLYING CHILDREN'S RECALL OF SENTENCES

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Abstract

It has been found that an information-processing analysis of latencies collected in an immediate sentence recall task using children with median age 4 yr 4 mo favors a serial processing mechanism which consists of three major parts: the detection of a clausal boundary, the assessment of whether or not the observed noun-verb-noun structure satisfies a unique semantic constraint (in terms of the meaningfulness of interchanging its two clausal nouns), and the assessment of whether the observed surface sequence satisfies a canonical order of subject-verb-object.

A Latency Analysis of Strategies Underlying Children's Recall of Sentences[1]

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Recent studies in psycholinguistics have emphasized that lexical <u>knowledge</u> (about potential deep structure) and <u>strategies</u> (such as finding cues to deep structure in the surface structure of sentences) can be demonstrated to influence the speed and accuracy with which we comprehend sentences (Fodor & Garrett, 1967; Fodor, Garrett, & Bever, 1968). Bever (1970) in a comprehensive review of psycholinguistic studies has enlarged upon this conception by stating a number of perceptual strategies which he believes are used to facilitate sentence comprehension.

The present paper extends this new theoretical emphasis by investigating the manner in which some of the perceptual strategies discussed by Bever combine to yield an analysis of the information-processing steps which subjects use to arrive at the semantic and syntactic relationships that hold in simple single-clause sentences. We shall argue that a more adequate theory of sentence comprehension than has hitherto been suggested must deal with the following: (1) how many strategies are at work in interpreting particular sentences and which ones are they?, (2) how are these several strategies combined so as to yield a sentence interpretation; that is, are these strategies combined in serial or parallel fashion, and, if serial, in what order?, (3) what are the number of possible outcomes for each strategy?, and (4) how can one unambiguously state the ways in which a number of different sentence types are processed by application of these several possible strategy combinations?

<u>Semantic and Syntactic Strategies</u>

Bever (1970) suggested that both semantic and syntactic strategies are used to facilitate sentence comprehension. Three of his strategies are of prime importance for us here. The first has to do with detecting the end of a clause. In this paper we shall be dealing with single-clause sentences and hence the end of the clause coincides with the end of the sentence. Bever has suggested that many studies indicate that only after we have detected the end of clauses do we begin to think about what we have just heard. The end-product of this thinking is the determination of the deep structural relations that hold among the key content items in the clause--the key content items being here the nouns and verb in the clause that were superficially analyzed while the sentence was being read to us. That is, we detected that a noun, a verb, and another noun were form classes used in the clause, and this detection of the word classes along with the falling intonation at the end of the sentence helped us to determine that a clause had occurred. Only after this clause has been isolated do we begin to untangle the deep structural relations (subject, verb, and object relations) that hold among these surface elements.

On the assumption that real time is needed to arrive at the deep structural relations, if we measure the time from when the stimulus sentence ends to when the subject begins his response, we shall have a measure of how long it took the subject to arrive at the deep structural relations in the clause.

A second strategy deals with semantic restrictions (Bever, 1970, p. 296). When the constituents in a clause are semantically related according to learned functional constraints, then it is assumed that the subject is capable of using this information in order to assign a deep structure to the verb and two nouns of the clause which he has just heard (or to a single noun and verb of a clause, as in the case of truncated passive clauses, for example). Young subjects are capable of differentially responding to such semantic restrictions as reported by Turner and Rommetveit (1967). For example, they found that semantically reversible active sentences (A_r) are significantly more difficult than nonreversible active sentences

(A_{nr}). As examples: an A_r sentence would be "The lamb likes the dog" inasmuch as the two nouns can be reversed and still lead to a meaningful sentence; however, with A_{nr} sentences this is not so. In "The man throws the brick" we cannot interchange the two nouns and still get a meaningful sentence. Turner and Rommetveit also found that reversible passives (P_r) were significantly more difficult than nonreversible passives (P_{nr}). In summary, Bever's semantic order strategy is just another way of saying that a subject notices and is behaviorally influenced by reversible versus nonreversible sentence types.

The third and final strategy of Bever's which we shall need has been called a canonical order strategy (Bever, 1970, p. 298). This means that when a subject detects a noun-verb-noun sequence in the surface structure of a clause, it is often the case that this ordering will correspond to a subject-verb-object ordering in terms of the deep structural relations. Bever indicated that children who are first learning and using this strategy will incorrectly regard full passives as though they were actives. However, with increasing age this canonical order strategy is not applied indiscriminately. That is, we should allow for the possibility that while a noun-verb-noun sequence may at first be hypothesized to follow just the subject-verb-object ordering (due to its preponderance in the language), older subjects will not invariably be trapped into regarding every such occurrence as an active sentence.

In summary, we have selected three perceptual strategies of Bever for special study in constructing explicit information-processing models of the comprehension process in real-time. What remains to be done is to indicate how these strategies are combined (serially or in parallel fashion), the decision outcomes that are possible following the application of each perceptual strategy, and how each of the several sentence types (A_r, A_{nr}, P_r, P_{nr}, as well as truncated passives P_t which delete reference to the logical actor of a sentence as in "The phone was broken") is differentially processed by the model(s).

Before we take up the specifics of the models it will be necessary to touch upon a number of related issues. One might anticipate (Smith, 1970, p. 132) that truncated passives may be easier to comprehend than full passives since they do not appear to involve any possibility of semantic reversibility confusion inasmuch as only one noun and one verb are used. However, there is some question as to why one should think that young children will necessarily recognize truncated passives to be passives; that is, it seems possible that young children may interpret truncated passives as if they were active sentences. For example "The girl was named Mary" could be interpreted to mean "The girl's name is Mary" which is an active sentence. Indeed the meanings are identical except that the notion of a missing agent has been lost in the active representation. Partial evidence that this may be occurring comes from a study by Slobin (1968). Inspection of his tabulated results (Slobin, 1968, p. 878) suggests that the three youngest age groups (5-, 6-, and 8-yr-olds) recall truncated passives told in story form as active-type sentences more often than they recall them in true truncated form, whereas the three oldest groups recalled truncated passives more often in correct truncated form rather than in active sentence forms. This difference with respect to age did not occur in recalling stories told in full passive voice. While this evidence is not conclusive, it does raise the possibility that very young children may incorrectly perceive truncated passive forms as if they were active-type sentences. If this were true, one might anticipate that the time it takes to begin a recall of a truncated passive sentence would be equivalent to the time it takes to begin recall of true active sentences: P_t would then be equal in difficulty to A_{nr} sentences. But if P_t sentences are correctly perceived, then they should be about [illegible]al in difficulty to P_{nr} sentences.

Latency Models

Strategies in a Serial Processing Model

Figures 1A and 1B show how we can combine the three Bever strategies into

Insert Figure 1 about here

a serial decision tree so as to predict the latency with which each of our five sentence types tend to occur. We shall assume that the identification of the clausal boundary, which occurs for every sentence type and is cued by the falling intonation of the experimenter as he reads each sentence, can be accounted for by a fixed delay of value k. That is, we assume that a small but fixed amount of time is taken up in identifying that a clause boundary has occurred. Once a clause has been isolated this functions as a cue to begin further processing of the semantic and/or syntactic information in the clause. According to Fig. 1A the next decision that is made is to decide whether the two nouns in the clause have a unique semantic ordering in terms of which is most likely to function as the actor of the clause. If the subject sees that only one of these nouns can function as the actor in order for the clause to make sense, then we assume that he invokes Bever's semantic strategy and assigns a subject-verb-object ordering according to these perceived semantic constraints. He need not analyze the clausal structure further in terms of its syntactic structure since he already possesses sufficient information to assign a deep structural relation among the clausal elements. We see that according to Fig. 1A there are three sentence types which fulfill this semantic strategy: A_{nr}, P_{nr}, and P_t. Naturally, if we present many exemplars of the A_{nr} type (and many exemplars of the other two types) we should not expect the observed latencies to be exactly the same value. We expect some variance to occur among the observed latencies. To account for such variance it is necessary to make some assumptions about the underlying form of the latency distribution that characterizes each step of the decision

We shall assume here, as well as for all the remaining models, that each branch (except the identification of the clausal boundary which consumes a fixed amount of time, k) is described by a simple exponential function, ae^{-at}. In the exponential distribution, there is a constant conditional probability that the process will end in the next time instant given that it has not already ended (see McGill, 1963, and appendix to this paper for further details).

We note that the time constant a that occurs for one of the branches of the decision tree in Fig. 1A bears a simple relationship to the mean of all the sentence types that must traverse this pathway. The simple exponential has a mean equal to 1/a. Thus once the value of a has been estimated we can use this to predict the mean amount of time taken up by deciding that a particular sentence satisfies the unique semantic ordering strategy. Since every sentence that traverses this a branch has also passed through the fixed delay k we see that both these values must be added to account for the observed mean latency of sentences which have unique semantic constraints. Fig. 1A indicates that since sentences A_{nr}, P_{nr} and P_t are all semantically constrained and since no further processing of the structure is assumed to take place, all these sentences should have virtually identical mean latencies. The value of this mean latency is simply the sum of times it took to traverse each branch: $1/a + k$.

Of course not all the sentences which we will present will satisfy the semantic strategy. In particular A_r and P_r sentences will not pass the test of a unique semantic constraint since both nouns can function equally well as the sentence actor. But it takes time to decide that the semantic order strategy will not work. We again assume that a simple exponential distribution describes the time that it takes to decide "no" a unique semantic ordering does not hold for a given sentence. In Fig. 1A we assign the time constant b to describe the exponential decision time for this pathway.[3] Since the semantic strategy did not work for A_r and P_r sentences, the subject must find some other way to interpret the deep structure of the sentences. His next strategy is to test whether or not the noun-verb-noun sequence in the surface clause satisfies the canonical order strategy of subject-verb-object. Only one of these types will satisfy this strategy: the A_r sentences. Since the mean time it takes to decide "yes" the canonical order holds is equal to $1/c$, and since pathway b as well as k have also been traversed in assigning a structural description to A_r sentences, we see that the mean latency for A_r sentences is $1/b + 1/c + k$. By a similar argument the mean time to assign P_r a structure is $1/b + 1/d + k$. It is assumed that whenever the subject decides that canonical order does not hold he automatically realizes that the correct ordering is object-verb-subject. For each of the sentence types when all the processing steps indicated by Fig. 1 have been completed the subject begins his overt recall of the sentence.

Now that we have devoted considerable detail in describing the meaning of each of the steps that occur in the decision tree for model 1A, it is quite simple to describe the model given in Fig. 1B (the Redundant Check Serial Model). We note that the only difference between models 1A and 1B is that following the pathway labeled a we allow for further syntactic processing to take place. Thus model 1B is in some sense a redundant check model because it assumes that the subject will double-check the adequacy of his deep structural assignments which resulted from a "yes" decision of the semantic ordering strategy by carrying out a syntactic assessment of the noun-verb-noun sequence. We see that A_{nr} and P_{nr} sentences in model 1B can now have quite different mean latencies inasmuch as they traverse somewhat different pathways. A_{nr} sentences move through paths k, a, and c while P_{nr} sentences move through k, a, and d. It is also immediately apparent from Fig. 1B that A_r and P_r sentences are given exactly the same interpretation as they were assigned by model 1A. The only sentence type that presents a problem here is P_t. We see that a decision has to be made as to whether they will follow a pathway similar to A_{nr}

or P_{nr} types. Since we cannot make this assignment from a priori considerations, we must let the data tell us what the most likely interpretation is.

Perceptual Strategies in Parallel Processing Models

The two models just discussed have been labeled as primarily serial processing models. Bever (1970, pp. 296-297) cites data which suggest that semantic and syntactic decision may sometimes be carried out simultaneously, that is, in parallel fashion. Using the same three basic strategies as employed in constructing our serial models, we shall formalize two latency models that involve a parallel decision process.

In Fig. 1C we see that the time it takes to identify the clausal boundary is again assigned a fixed value of k. We again assume that the time it takes to make a decision about each pathway can be best described by a simple exponential distribution. Moreover, just as before, when we had a nonredundant model which allowed for some sentences to be fully interpreted by just a semantic ordering strategy, so now we allow for a similar conceptualization to hold in a parallel processing model.

The model sketched in Fig. 1C allows for semantic and syntactic information to be processed simultaneously. In particular A_{nr} sentences by this model can now be interpreted by one of two ways: either the a branch interprets it (i.e., a "yes" for the unique semantic ordering strategy occurs first and it suffices to interpret A_{nr} deep structure) or a c branch interprets it (i.e., a "yes" for the canonical order strategy occurs first and this suffices to interpret the sentence). If we presented many such A_{nr} sentences some of them will have been interpreted by the a branch and some by the c branch: the possibility of having two equally viable ways to interpret the same sentence structure is reflected in the theoretical mean of A_{nr} sentences which Fig. 1C gives as $k + 1/(a+c)$. Similarly, P_{nr} sentences can be interpreted by either of two parallel pathways: an a branch or a d branch. The decision as to what pathways will be followed by P_t sentences must again await examination of the data.

Fig. 1C also indicates that A_r sentences are interpreted by only a single branch, the c pathway (and that P_r sentences are interpreted by only the d pathway). The reason that only a single pathway is involved in this particular parallel search model is as follows. We no longer have a truly functional b pathway which signifies that the subject decides "no" a particular sentence does not have a unique semantic ordering. Any reversible sentence which is first assigned a nonunique semantic ordering by the parallel processing mechanism cannot lead to a sentence interpretation in and of itself; rather, it must await completion of the syntactic decision mechanism that has not yet outputed its decision before sufficient information has been processed to uncover this sentence's deep structure. This state of affairs is indistinguishable from one where only a syntactic branch is used to assign a deep structure. Hence, the b branch is totally nonfunctional in a parallel processing mechanism that requires that the first channel to output will be the one which determines the structural description of the sentence under consideration.

On the other hand Fig. 1D presents a second parallel model which requires an output from both semantic as well as syntactic decisions before sufficient information has been gathered to interpret the stimulus sentence. Because not every sentence type really requires both a semantic as well as syntactic decision to be made in order to interpret its deep structure we are again dealing with a kind of redundancy check model--a parallel redundancy check model Fig. 1D shows that the b branch of the semantic decision tree is again viable under the assumptions of this parallel model. In order to interpret A_{nr} sentences the subject must await a "yes" outcome from the semantic decision as well as a "yes" outcome from the syntactic decision. P_{nr} sentences must await a decision from the a and d branches; A_r sentences require both the b and c branches to have outputed, while P_r sentences require a b as well as d branch to have an output. P_t sentences again have an ambiguous state. The general formula for calculating the means and variances of this second parallel model are found in Fig. 10.[4]

The Experiment

Method

Materials. Twenty sentences were presented to each of 31 subjects. Four exemplars of each of five sentence types were constructed. Table 1 presents the list of sentences. The order of these sentences was randomized within each of

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Insert Table 1 about here
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two test forms. The second test form was constructed from the first by converting all A_{nr} sentences of Form 1 into P_{nr} sentences; also A_r sentences were converted into P_r sentences, P_{nr} into A_{nr}, and finally P_r were converted into A_r sentences. Different exemplars of P_t sentences were used in the two forms in order to increase the number of exemplars investigated in this infrequently studied type. Further one can see in Table 1 that A_{nr}, P_{nr}, and P_t sentences allow for a contrast between using an inanimate versus an animate count noun as the logical objects of sentences.[5] All nouns used as logical subjects were animate count nouns.

Procedure

Thirty-one subjects from a nursery school in the Princeton area were tested (17 males, 14 females). The subjects were white middle-class children with English as their native language. The subjects ranged in age from 2 yrs 7 mo to 6 yrs 2 mo with a median of 4 yrs 4 mo.

The two forms were used in alternation as each subject arrived for testing. Testing took approximately 15 minutes for each subject. Each subject was given three short sentences as a warm-up prior to beginning the testing proper. If the subject failed to say all the words in these warm-up sentences, he was asked to try again following another repetition of the stimulus sentence. The examiner read the sentences with natural intonation. Each subject was tested individually.

Instructions. The subjects were read the following instructions: "I am going to say some things and I want you to say the same things that I say." This was followed by the practice sentences which were each preceded by the special instruction "Say, ... " During the experiment proper none of the sentences were prefaced by "Say,...." Frequent encouragement was given the child in order to maintain his interest in the task. If a child failed to say all the key words in the sentence on his first attempt at recall, he was read the same sentence and asked to try again. This was done so as to discourage fragmentary responding on their first attempts at recall. The entire session was tape-recorded for each child.

Scoring of latencies and errors. Following a typed transcript of each child's session, two judges[6] used stopwatches and timed the interval between the end of the stimulus sentence and the beginning of the subject's utterance. The tape recordings were played back at one-fourth their original speed so as to increase the accuracy of the recorded latencies. Ninety percent of the two judges' time scores were within .05 sec (real time) of each other. The mean of the two judges' scores was averaged and used as the final estimate for each sentence. Two judges independently transcribed the recorded session for each child. These transcriptions were used to conduct an error analysis for the recall of articles, nouns, and verbs. In general, these error analyses were intended as supplementary to the major effort of analyzing the latency distributions; the relationship between errors and latencies will be discussed in later sections of this paper. Only first attempts at recall were used the analyses which follow.

Results

Latency analysis for each of the four latency models. The observed means and variances were computed for each of the five sentence types. These are given in Table 2. We see from the table that the relative order of difficulty, as revealed by the mean latencies, was: A_{nr}, P_t, A_r, P_{nr}, and P_r.

Insert Table 2 about here

Also from the table it can be seen that the variance tends to increase as the means increase; such a relationship is expected on theoretical grounds, as the reader can determine from examining the close relationship between theoretical means and variances for each of the four models given at the bottom of Fig. 1. Before the reader can understand how these theoretical means and variances were arrived at he must know how the parameters for each branch of the decision tree were estimated for each of the four models.

The fixed delay $\underline{k}$ for each of the four models was estimated by examining the smallest order statistic that resulted for each of the five sentence types. These values were as follows: .225 sec, .262 sec, .250 sec, .262 sec , and .250 sec, for A_{nr}, A_r, P_{nr}, P_r, and P_t, respectively. Since each of the latency models asserts (by assumption) that this value $\underline{k}$ should not depend upon the sentence type (that is, it should be approximately the same magnitude for each sentence type, which it appears to be) the average of these five estimates of $\underline{k}$ was used as the best estimate of the fixed delay for each sentence type and for each of the four latency models. Thus $\underline{k}$ = .250 sec. In order to estimate the time constants $\underline{a}$, $\underline{b}$, $\underline{c}$ and $\underline{d}$ for each model it was necessary to compile ~~extensive~~ tables which showed the theoretical means and variances for particular combinations of any two time constants which varied in value over a wide range. After subtracting the estimated value of $\underline{k}$ from the observed mean for each sentence type, this table was searched until a combination of parameter values was found which matched the observed mean (corrected mean) and the observed variance. Depending upon which model was being fitted at a given time, it was possible that several estimates of a particular parameter would result from the table look-up procedure; when this occurred the mean time constant was used as the final estimate of the parameter. For example, model 1B in Fig. 1B indicates that sentence A_{nr} as well as sentence P_{nr} both involve the time parameter a. The mean of these two time estimates which resulted from the table look-up procedure was used as the final estimate of a. Using model 1B two estimates of a, b, c, and d were obtained. The final values were: k = .250 sec, a = 6.90 (which has a mean expected duration of .145 sec because the mean of the exponential for each branch of the decision tree is 1/a = .145 sec), b = 5.05 (mean = .198 sec), c = 5.75 (mean = .174 sec), and d = 3.80 (mean = .263 sec). The parameters from sentence type P_t did not enter into the above computations because of its ambiguous status in terms of the a priori uncertainty as to whether it is interpreted as an active or passive sentence. In the chi-square analysis which used the above five parameter values, however, it was quite clear that a better fit resulted if one regarded P_t sentences as being interpreted as active sentences (this was true of each of the four latency models).

The chi-square test was made possible by application of the cumulative distribution function for each sentence type (see appendix). The best fitting model was the redundancy check serial model--its chi-square fit was 29.55 ($.10 < p < .20$, 23 df). As one can see from inspection of Table 3 the next best fitting model is the

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Insert Table 3 about here

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redundant check parallel model which gave a chi-square of 34.43 ($.05 < p < .10$, 23 df). It is noteworthy that two conceptually very different models can yield rather similar chi-squares. The two worst fitting models are the nonredundant serial and nonredundant parallel models which each yield an unacceptably low p value beyond the .0001 level as shown in Table 3.

The effects of animate versus inanimate objects on latencies. A question can be raised as to whether semantic reversibility effects should be more easily arrived at (yield faster latencies) when the logical object of a sentence is an inanimate count noun versus when it is an animate noun. More specifically, one is struck by the fact that reversible sentences more often than not will contain two animate nouns while animateness appears to be less of a constraint in constructing nonreversible sentences. It may well be that decisions regarding semantic reversibility will be facilitated by recognizing whether both nouns are classified as animate or not, while nonreversible sentences with one inanimate and one animate noun will be evaluated for semantic reversibility in other as yet unspecifiable ways. Should this be the case it would shed light on at least one aspect of the sentence structure which contributes to decisions regarding semantic reversibility effects. To evaluate this conjecture the A_{nr}, P_{nr}, and P_t sentences were divided into two subgroups each: those latencies associated with animate objects and those latencies associated with inanimate objects. No significant difference was found ($p > .25$, 1-tailed) for all three comparisons of these sentence types. This suggests that our young subjects were unable to make use of the constraint (strategy) that sentences having both animate subject and object are likely to be semantically reversible sentences; of course, the failure of this comparison leaves open the question as to just how such reversibility decisions are arrived at. The classification of semantic relations used in studies by David Meyer (1970) suggests one possible route in exploring this problem further.

Age effects on means and variances of latencies for the five sentence types. Mann-Whitney U-tests were used to evaluate whether the younger half responded significantly slower to each sentence type. The only sentence type that approached significance was P_t sentences ($p = .10$, 1-tailed) which yielded .652 sec for the younger on P_t sentences versus .517 sec for the older. Similar Mann-Whitney U-tests were applied using the variances of each sentence type for each subject. Again P_t sentences were found to be significantly different across the two age groups: the younger subjects were significantly more variable in their latencies to P_t sentences than were the older subjects. The younger subjects gave a variance score of .125 while the older gave .024. All other sentence types were not significantly different across the two age groups ($p > .10$ in all comparisons, 1-tailed). These results for P_t sentences suggest that the younger subjects are somewhat more uncertain of the meaning (or structural significance) of P_t sentences and perhaps waver between several interpretations of these structures.

<u>Errors in sentence recall and its effect on latency.</u> There are several problems that arise regarding the latency models. Not every sentence that the subject recalls is error-free; sometimes words are omitted, sometimes substitutions occur, etc. The problem this poses is whether an error that occurs in the recall phase <u>necessarily</u> reflects back upon the latency interval that <u>preceded</u> it. If it does, then this must call for a more restricted data base on which to assess the latency models. One might anticipate that a long latency might occur if the subject detected an error in his memory for the sentence, for example. To examine this possibility the transcripts of each subject were examined for omissions of the content words, nonsynonymous substitutions of the content words, and/or syntactic transformations. The mean latencies for sentences which contained errors in recall were .733 sec, .665 sec, .667 sec, .528 sec, and .619 sec, for P_r, P_{nr}, A_r, A_{nr}, and P_t sentences, respectively. These means are to be compared with the unconditional mean latencies (irrespective of whether an error occurred or not in recall). These means were: [illegible]08 sec, .669 sec, .632 sec, .563 sec, and .582 sec for P_r, P_{nr}, A_r, A_{nr}, and P_t

sentences, respectively. There is no systematic difference between these two arrays. In other words, this suggests that the occurrence of an error in recall following the latency interval does not contain useful information about the occurrence or nonoccurrence of a long latency. Had we found such a systematic effect it would have been necessary to evaluate the latency models using only those latency scores which preceded a correct recall.

Discussion

The above analyses, especially with regards to evaluating which of the four latency models best fits the data, can be taken as providing further support for the new emphasis in theoretical psycholinguistics which highlights the importance of a language user's knowledge and strategies that he brings to bear in processing sentential information. In particular it appears that Bever's strategies of clause isolation, semantic restrictions, and canonical order provide us with adequate building blocks with which to fashion more explicit information-processing models as exemplified by the serial and parallel processing models. It is possible, of course, that when more complex sentences (such as right-branching, self-embedded, or left-branching structures) are presented, one will have to consider a more complex network of strategies as operating to uncover the deep structural relations among the several clauses as well as within each clause. This remains to be seen. The point of what has been accomplished thus far is that, by virtue of using simply structured single-clause sentences as stimuli, we have been able to posit several reasonable information-processing approaches which occur in interpreting sentence deep structure. By testing the implications of these several models we have been able to isolate one as providing the best fit to the data. In choosing which model best fit the data it was necessary to use all the information that the data provided us with--namely, the mean, variance, and distributional form. Just evaluating the means of the several models cannot provide us with a clear-cut procedure for choosing among them. The observations raise several important implications which relate to recent attempts to model the manner in which language users compare sentential information against pictorial information (Chase & Clark, 1970; Trabasso, 1970, Trabasso, Rollins & Shaughnessy, 1971). Let us consider the relationship in greater detail.

Mental operations in comparing sentences and pictures. Several methods have been used to study the comparison processes for sentential and pictorial information; the one which will prove most relevant to us here is the method that separates the presentation of the sentence from the pictured event. In one condition the sentence is presented first, then there is a long pause of perhaps five seconds, and finally a picture is presented which either affirms the sentential information or contradicts it. In another condition the picture is seen first and then the sentence description follows which either affirms or contradicts the information in the picture. These two procedures make a difference in terms of the time it takes to arrive at a judgment that the two events match (are "true") or mismatch (are "false"). The second condition it would seem confounds the time it takes to understand the sentence (usually the subjects read the sentence) with the time it takes to compare the two events. When the subject reads a sentence the time it takes him to comprehend it is not under direct control; however, if the subject were read the sentence by the experimenter, then we suggest that in this case one is in a better position to evaluate comprehension time. To see this consider the following procedure. Suppose that before the experiment is run each subject is run in a sentence recall task just as our children were in the above study. This procedure will allow one to measure the comprehension time for a variety of sentence structures. Once the time parameters have been estimated one can then study the comparison process between sentence and picture and attempt to extract out the time it takes to comprehend each sentence in the comparison task by using the information gathered from the separate sentence recall condition. Having used the latency models to study the sentence comprehension time, though, raises a further interesting possibility. We have developed the theoretical apparatus for selecting the best-fitting serial versus parallel processing models for sentences; why not use the same theoretical apparatus to enrich our understanding of the sentence-picture comparison processes as well? The comparison models espoused thus far are of the serial processing type. Our depth of understanding of the comparison process would be greatly enhanced by allowing for the further possibility that the comparison of inner and outer strings (of the Response Change Model discussed by Trabasso, 1970) are carried out in parallel processing fashion. Indeed, there is a remarkable similarity between these two comparisons of the inner versus outer strings and the abstract decision tree structure for semantic and canonical order strategies. Briefly, the similarity is this: if the inner strings don't match, some additional processing has to be carried out before one can arrive at a decision; this is analogous to our serial nonredundant processing model which said that if the semantic ordering decision fails, then additional processing has to be carried out to arrive at the deep structural description. If the inner strings match (again according to the serial nonredundant model) the subject terminates the processing and says "true." In the sentence model this is analogous to saying that when the unique semantic ordering strategy which is applied first yields a "yes" decision, then the subject has sufficient information to recover the deep structural relations and at this point begins his overt recall of the sentence. The analogy also partially holds up when we attempt to study the comparison process as though the inner and outer strings were evaluated simultaneously in time, i.e., in parallel fashion. Just as before, we can postulate that there may be two possible parallel models of interest--a redundancy check parallel model which requires a decision output from both inner and outer string channels before an overt response is made, or a nonredundant check parallel model. The degree to which we can enrich these comparison models does not end here for it must be mentioned that by considering the fitting of these serial and parallel models not only to the sentence comprehension portion of the picture-sentence comparison task but to the decision times involved in the comparison process itself, we shall be using not only the means and variances of these decision times, but in addition, will be using the full distributional forms. Previous evaluations of the serial comparison models have focused upon just the mean decision time.

Outline of a more complex latency theory when sentence information is incorrectly perceived. We mentioned that subjects may not always correctly perceive the semantic and/or syntactic structure of sentences which they are asked to recall. While the above latency data failed to reveal any systematic relationship between explicit recall errors and the duration of the latency interval that preceded the recall, nevertheless it will be fruitful to consider just how one can handle the problem posed by incorrect perceptions of sentence structure and the effect it can have on latency distributions. We shall for convenience consider only the four sentence types A_{nr}, A_r, P_{nr}, and P_r.

Suppose that on a certain proportion of trials a semantically reversible sentence is thought to be a nonreversible structure by some subjects. We shall not speculate here as to why this may happen--we only allow that such an error can occur. If we postulate for the moment that only semantic classification errors occur and not syntactic errors, then we can easily construct a confusion matrix which summarizes the proportion of time that a given stimulus structure will be correctly perceived as semantically reversible (or nonreversible) and the proportion of time that it is incorrectly perceived as nonreversible (or reversible).

Insert Table 4 about here

Table 4A shows that with probability p sentence type A_{nr} will be correctly perceived as semantically nonreversible, but with probability 1-p it will be incorrectly classified as an A_r sentence. Still concentrating our attention on A_{nr} sentences, let's investigate what effect such a perceptual error will have on the latency distribution for A_{nr} sentences. For the redundant check serial model the hypothetical density of A_{nr}, assuming that A_{nr} is confused with A_r with probability 1-p, is:

$$f(t)_{A_{nr}} = p\left[\frac{ac}{a-c}\,(e^{-ct} - e^{-at})\right] + (1-p)\left[\frac{cb}{c-b}\,(e^{-bt} - e^{-ct})\right].$$

[Notice that if A_{nr} were never confused with A_r sentences (i.e., if 1-p = 0.0) then the second term of the above equation would drop out.] This density would have a mean latency equal to $p(1/a + 1/c + k) + (1-p)(1/c + 1/b + k)$. (By referring to the densities in the appendix for each of the sentence types under each of the four different latency models, the reader should be able to extrapolate from the above example and work out the implications for the densities for each of the remaining rows of Table 4A.)

If we wished to complicate matters even more, one could allow for the possibility that syntactic confusion also occurs along with semantic confusions. For clarity, let us first assume that active sentence constructions are confused with passive structures independently of their semantic reversibility classification--let this syntactic confusion occur with probability 1-r. Also let's assume that semantic reversibility errors are made independently of the syntactic form--let this semantic error occur with probability 1-p. Finally, assume that it is just as likely that an active sentence will be misinterpreted as a passive form as it is for a passive to be misinterpreted as an active--we also make a similar symmetry assumption for reversible and nonreversible semantic structure. Under these assumptions we can te the confusion matrix as given by Table 4B.

If this were a correct representation of the confusion proportions for, say, the P_r sentences and <u>if</u> one had independent estimates of the latency time parameters for just the correct sentence types, then we could write the density of P_r sentences using the nonredundant parallel model as:

$$f_1(t)_{P_r} = rp(de^{-dt}) + r(1-p)(a+d)e^{-(a+d)t} + (1-r)pc\; e^{-ct}$$

$$+ (1-r)(1-p)(a+c)e^{-(a+c)t}.$$

What this shows is that each of the sentence types that can be confused with the stimulus sentence gets its density weighted by the probability that this confusion will occur over the entire experiment. If no confusions at all occurred, then this equation would simplify to $f_1(t)_{P_r} = d\, e^{-dt}$. What we have outlined above, then, is a very general latency model which allows for incorrect perceptions to occur among the set of sentence types used in a fairly restricted experimental setting. The difficulty with postulating such general models is that one must have some independent way to assess the degree to which each of the possible perceptual confusions can occur; needless to say this problem is not easily solved. We shall have to rest content that at least the essential nature of this more general latency problem can be clearly stated, as we have just attempted to demonstrate.

Conclusions and Summary

1. It has been found that an information-processing analysis of latencies collected in an immediate sentence recall task using children with median age 4 yr 4 mo favors a <u>serial</u> processing mechanism which consists of three major parts: the detection of a clausal boundary, the assessment of whether or not the observed noun-verb-noun structure satisfies a unique semantic constraint (in terms of the meaningfulness of interchanging its two clausal nouns), and the assessment of whether the observed surface sequence satisfies a canonical order of subject-verb-object.

2. An age effect was found for just the truncated passive sentences which suggests that younger subjects (ranging in age from 2 yr 7 mo to 4 yr 4 mo) are significantly more variable in their response latencies (and possibly significantly slower in their mean response latency) in comparison with the older subjects (ranging from 4 yr 4 mo to 6 yr 2 mo). An age effect did not show up for the remaining four sentence types: nonreversible actives, reversible actives, nonreversible passives, and reversible passives.

3. The latency models all favored the assumption that truncated passives were interpreted as nonreversible active sentences when the grouped data were assessed by a chi-square analysis; this result would appear to be in partial agreement with some results reported by Slobin (1968) regarding the differential effects of recall of full passives versus truncated passives for several age groups. However, the above finding must be considered tentative in view of the significant effect of the age variable on the latencies for recalling truncated passives.

4. An application of the theory of serial and parallel latency distributions with the purpose of further enriching the information-processing apprcaches to modelling the mental processes involved in matching sentential against pictorial information was outlined.

5. An extension of latency theory to handle situations wherein perceptual errors in the classification of the sentential information are hypothesized to occur was developed.

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Footnotes

[1]This research was supported, in part, by Grant 5-P01-HD01762 from the National Institute of Child Health and Human Development to the Educational Testing Service, Princeton, N.J.

[2]The authors wish to thank Margaret N. White and James Tittemore for assisting with many phases of the data collection and data analyses.

[3]The astute reader will recognize that what has been presented here as a "pure" serial model is actually more correctly designated as a mixture of a parallel process embedded within a serial one. That is, while the three Bever strategies are truly arranged in a serial manner, the binary decisions that are made (following the semantic and syntactic strategies) can actually be considered to be evaluated simultaneously in time such that only one of the two branches will "interpret" a particular sentence type. This way of stating the model(s) actually leads to a simpler latency process than would be the case had we entertained the idea that first a "yes" decision is evaluated, followed by the "no" branch being evaluated; indeed, it would be hard to justify such an awkward ordering on any logical grounds.

[4]One might think it necessary to postulate an additional processing step so as to merge the two pieces of semantic and syntactic information for this particular parallel model--but this is not necessarily the case. For example, A_{nr} sentences can have the a branch yield an output before the c branch. In such a case while one is awaiting the c branch to output, a tentative deep structure analysis can be arrived at because the a branch which has just fired indicates a unique semantic ordering; thus, once the c branch finally yields

its output, it will agree with the information tentatively arrived at by the _a_ branch. The same agreement between the output of the two branches is forthcoming if we assume that the _c_ branch fires before the _a_ branch. Even if we allow for the possibility that a small but fixed delay _k'_ is taken up in noticing that the two outputs agree, even this will not change the formal structure of our model(s) since the delay _k'_ will simply be absorbed into the overall estimate of the delay _k_. Further analysis of the possible outcomes for the other sentence types indicates that nowhere in this system will the outputs of the semantic and syntactic channels be incompatible--thus even if we allowed for such a comparison process to be made it would serve no useful purpose for the types of sentences we are considering here.

[5] A rationale for this contrast is provided in the result section.

[6] The two judges were Margaret N. White and James Tittemore.

Table 1

Test List 1	Test List 2
Nonreversible Actives	Nonreversible Actives
The farmer digs the hole.	The clown paints the wagon.
The lady washes the dish.	The boy drops the box.
The frog catches the fly.	The bird eats the worm.
The girl rides the pony.	The mother carries the baby.
Reversible Actives	Reversible Actives
The teacher helps the girl.	The dog chases the lamb.
The spider hurts the snake.	The pig follows the turkey.
The doctor visits the boy.	The boy kicks the pony.
The father kisses the mother.	The cow likes the horse.
Nonreversible Passives	Nonreversible Passives
The wagon is painted by the clown.	The hole is dug by the farmer.
The box is dropped by the boy.	The dish is washed by the lady.
The worm is eaten by the bird.	The fly is caught by the frog.
The baby is carried by the mother.	The pony is ridden by the girl.
Reversible Passives	Reversible Passives
The lamb is chased by the dog.	The girl is helped by the teacher.
The turkey is followed by the pig.	The snake is hurt by the spider.
The pony is kicked by the boy.	The boy is visited by the doctor.
The horse is liked by the cow.	The mother is kissed by the father.
Truncated Passives	Truncated Passives
The phone is broken.	The table is used.
The chair is sold.	The bottle is broken.
The tiger is hurt.	The lion is hurt.
The nurse is helped.	The rabbit is helped.

Note.--The underlined words for nonreversible actives, passives, and truncated passives indicate inanimate logical objects; all other logical objects are animate.

Table 2

Observed and Predicted Means and Variances

for Each of Four Latency Models

Sentence Type[1]	Observed Mean	Nonredundant Serial Pred. Mean	Redundant Serial Pred. Mean	Nonredundant Parallel Pred. Mean	Redundant Parallel Pred. Mean
A_{nr}	.563 sec	.610 sec	.569 sec	.566 sec	.576 sec
A_r	.632	.634	.622	.606	.626
P_{nr}	.669	.610	.658	.653	.718
P_r	.698	.697	.711	.721	.697
$(P_t = A_{nr})$	.582	.610	.569	.566	.576

Sentence Type	Observed Variance	Nonredundant Serial Pred. Var.	Redundant Serial Pred. Var.	Nonredundant Parallel Pred. Var.	Redundant Parallel Pred. Var.
A_{nr}	.056 sec^2	.129 sec^2	.051 sec^2	.101 sec^2	.061 sec^2
A_r	.061	.075	.069	.128	.079
P_{nr}	.104	.129	.090	.163	.048
P_r	.085	.100	.108	.223	.115
$(P_t = A_{nr})$	.076	.129	.051	.101	.061

[1] A_{nr} = nonreversible actives; A_r = reversible actives; P_{nr} = nonreversible passives; P_r = reversible passives; P_t = truncated passives (in all cases assuming that P_t was interpreted as A_{nr} resulted in better fits for each model than assuming that P_t was interpreted as P_{nr}.

Table 3

Observed and Predicted Frequencies for Each of Eight Time Intervals for Each of Four Models

1. Redundant Check Serial Model

Parameters

k = .25 sec.
a = 6.90 (mean = .145 sec.)
b = 5.05 (mean = .198 sec.)
c = 5.75 (mean = .174 sec.)
d = 3.80 (mean = .263 sec.)

Time Interval (sec.)	A_{nr} obs.f	A_{nr} pred.f	A_r obs.f	A_r pred.f	P_{nr} obs.f	P_{nr} pred.f	P_r obs.f	P_r pred.f	$P_t = A_{nr}$ obs.f	$P_t = A_{nr}$ pred.f
.00 - .35	22	16.4	15	13.2	12	11.6	6	8.8	15	16.4
.36 - .45	25	28.0	20	32.1	21	21.9	15	18.1	27	28.0
.46 - .55	18	25.4	16	24.2	20	21.6	20	19.7	28	25.4
.56 - .65	19	18.9	22	17.2	21	18.3	20	17.8	20	18.9
.66 - .75	17	13.1	14	14.6	14	14.2	20	14.7	15	13.1
.76 - .85	7	8.5	17	10.3	11	10.6	17	11.7	8	8.5
.86 - .95	8	4.8	9	7.2	7	8.0	9	9.0	3	4.8
.96 +	8	10.1	11	13.6	18	17.6	17	24.0	8	10.1

Chi-Square = 29.55 ($.10 < p < .20$), 23 df.
(8-1)(5-1) - (5 parameters) = 23 df.

Redundant Check Parallel Model

Parameters

k = .25 sec.
a = 5.20 (mean = .192 sec.)
b = 3.85 (mean = .260 sec.)
c = 4.15 (mean = .241 sec.)
d = 3.00 (mean = .333 sec.)

Time Interval (sec.)	A_{nr} obs.f	A_{nr} pred.f	A_r obs.f	A_r pred.f	P_{nr} obs.f	P_{nr} pred.f	P_r obs.f	P_r pred.f	$P_t = A_{nr}$ obs.f	$P_t = A_{nr}$ pred.f
.00 - .35	22	16.9	15	13.5	12	13.0	6	10.4	15	16.9
.36 - .45	25	28.0	20	24.1	21	23.2	15	19.8	27	28.0
.46 - .55	18	24.4	16	22.9	20	22.0	20	20.5	28	24.4
.56 - .65	19	18.1	22	18.5	21	17.7	20	17.7	20	18.1
.66 - .75	17	12.6	14	13.6	14	13.4	20	14.1	15	12.6
.76 - .85	7	8.3	17	9.8	11	9.7	17	9.7	8	8.3
.86 - .95	8	5.5	9	6.8	7	6.9	9	9.4	3	5.5
.96 +	8	10.2	11	14.8	18	18.1	17	22.3	8	10.2

Chi-Square = 34.43 ($.05 < p < .10$),
(8-1)(5-1) - (5 parameters) = 23 df.

Table 3 (continued)

Observed and Predicted Frequencies for Each of Eight Time Intervals for Each of Four Models

C. Nonredundant Serial Model

Parameters

$k = .25$ sec.

$a = 2.78$ (mean = .360 sec.)

$b = 4.55$ (mean = .220 sec.)

$c = 6.10$ (mean = .164 sec.)

$d = 4.40$ (mean = .227 sec.)

Time Interval (sec.)	Sentence Type									
	A_{nr}		A_r		P_{nr}		P_r		$P_t = A_{nr}$	
	obs.f	pred.f	obs.f	pred.f	obs.f	pred.f	obs.f	pred.f	obs.f	pred.f
.00 – .35	22	30.3	15	12.4	12	30.3	6	9.2	15	30.3
.36 – .45	25	22.6	20	22.3	21	22.6	15	18.6	27	22.6
.46 – .55	18	17.4	16	23.1	20	17.4	20	20.1	28	17.4
.56 – .65	19	12.9	22	18.9	21	12.9	20	18.3	20	12.9
.66 – .75	17	10.0	14	14.8	14	10.0	20	14.9	15	10.0
.76 – .85	7	7.6	17	10.3	11	7.6	17	11.4	8	7.6
.86 – .95	8	5.6	9	7.4	7	5.6	9	9.0	3	5.6
.96 +	8	17.7	11	14.9	18	17.7	17	22.4	8	17.7

Chi-Square = 80.32 ($p < .0001$),
(8-1)(5-1) - (5 parameters) = 23 df.

D. Nonredundant Parallel Model

Parameters

$k = .25$ sec.

$a = 0.36$ (mean = 2.778 sec.)

$c = 2.80$ (mean = .357 sec.)

$d = 2.12$ (mean = .472 sec.)

Time Interval (sec.)	Sentence Type									
	A_{nr}		A_r		P_{nr}		P_r		$P_t = A_{nr}$	
	obs.f	pred.f	obs.f	pred.f	obs.f	pred.f	obs.f	pred.f	obs.f	pred.f
.00 – .35	22	34.0	15	30.3	12	27.4	6	23.4	15	34.0
.36 – .45	25	23.9	20	22.9	21	21.3	15	19.6	27	23.9
.46 – .55	18	18.1	16	17.2	20	16.5	20	15.2	28	18.1
.56 – .65	19	12.8	22	13.1	21	12.7	20	12.8	20	12.8
.66 – .75	17	9.7	14	9.8	14	10.3	20	10.0	15	9.7
.76 – .85	7	6.9	17	7.6	11	7.9	17	8.1	8	6.9
.86 – .95	8	5.0	9	5.6	7	6.1	9	6.6	3	5.0
.96 +	8	13.6	11	17.5	18	21.8	17	28.3	8	13.6

Chi-Square = 137.77 ($p < .0001$),
(8-1)(5-1) - (4 parameters) = 24 df.

Table 4A

A Confusion Matrix for Semantic Reversibility Errors

Response Type (Perceived Structure)

Stimulus Sentence Type	A_{nr}	A_r	P_{nr}	P_r
A_{nr}	p	1-p		
A_r	1-q	q		
P_{nr}			r	1-r
P_r			1-s	s

Table 4B

A Confusion Matrix for Both Semantic and Syntactic Confusions

Response Type (Perceived Structure)

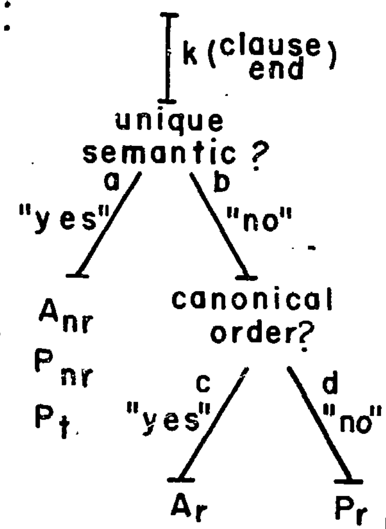
Stimulus Sentence Type	A_{nr}	A_r	P_{nr}	P_r
A_{nr}	r p	(1-p) r	(1-r) p	(1-r)(1-p)
A_r	(1-p) r	r p	(1-r)(1-p)	(1-r) p
P_{nr}	(1-r) p	(1-r)(1-p)	r p	r (1-p)
P_r	(1-r)(1-p)	(1-r) p	r (1-p)	r p

Figure Caption

Fig. 1. Four latency models.

SERIAL, NONREDUNDANT MODEL WITH ADDED CONSTANT

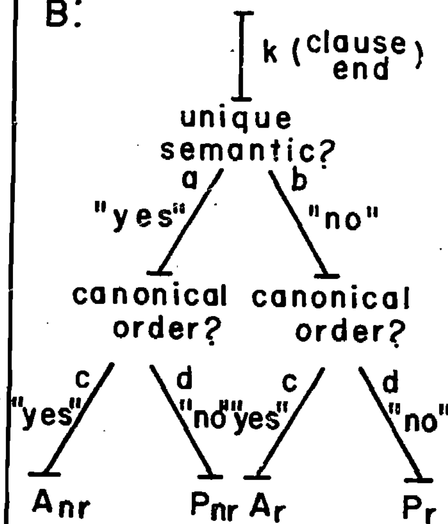
A:



Sentence Type	Mean	Variance
A_{nr}	$\frac{1}{a}+k$	$\frac{1}{a^2}$
A_r	$\frac{1}{b}+\frac{1}{c}+k$	$\frac{1}{b^2}+\frac{1}{c^2}$
P_{nr}	$\frac{1}{a}+k$	$\frac{1}{a^2}$
P_r	$\frac{1}{b}+\frac{1}{d}+k$	$\frac{1}{b^2}+\frac{1}{d^2}$
P_t	$\frac{1}{a}+k$	$\frac{1}{a^2}$

SERIAL, REDUNDANT CHECK MODEL WITH ADDED CONSTANT

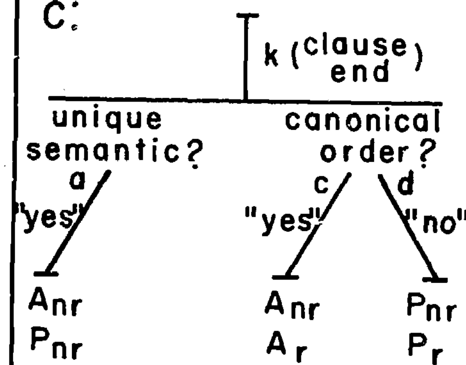
B:



Sentence Type	Mean	Variance
A_{nr}	$\frac{1}{a}+\frac{1}{c}+k$	$\frac{1}{a^2}+\frac{1}{c^2}$
A_r	$\frac{1}{b}+\frac{1}{d}+k$	$\frac{1}{b^2}+\frac{1}{d^2}$
P_{nr}	$\frac{1}{a}+\frac{1}{d}+k$	$\frac{1}{a^2}+\frac{1}{d^2}$
P_r	$\frac{1}{b}+\frac{1}{c}+k$	$\frac{1}{b^2}+\frac{1}{c^2}$
P_t	$\frac{1}{a}+\frac{1}{c}+k$	$\frac{1}{a^2}+\frac{1}{c^2}$
(P_t)	$\frac{1}{a}+\frac{1}{d}+k$	$\frac{1}{a^2}+\frac{1}{d^2}$

PARALLEL, NONREDUNDANT MODEL WITH ADDED CONSTANT

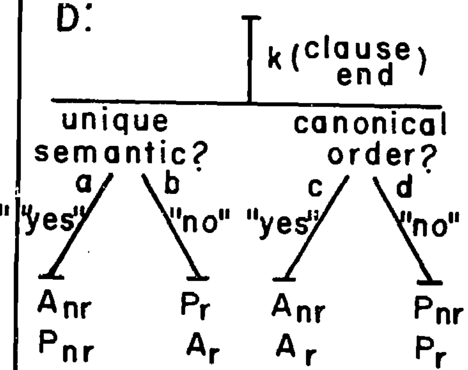
C:



Sentence Type	Mean	Variance
A_{nr}	$\frac{1}{a+c}+k$	$\frac{1}{(a+c)^2}$
A_r	$\frac{1}{c}+k$	$\frac{1}{c^2}$
P_{nr}	$\frac{1}{a+d}+k$	$\frac{1}{(a+d)^2}$
P_r	$\frac{1}{d}+k$	$\frac{1}{d^2}$
P_t	$\frac{1}{a+c}+k$	$\frac{1}{(a+c)^2}$
(P_t)	$\frac{1}{a+d}+k$	$\frac{1}{(a+d)^2}$

PARALLEL, REDUNDANT CHECK MODEL WITH ADDED CONSTANT

D:



Mean for any 2 time values x and y plus added constant k

$$= k + \frac{y^2(2x+y)+x^2(2y+x)}{xy(x+y)^2}$$

while variance about Mean is

$$= \frac{2}{x^2}+\frac{2}{y^2}-\frac{2}{(x+y)^2}-(\text{mean}-k)^2$$

Appendix

Formulas for the Nonredundant Serial Model

Sentence A_{nr} has density $f(t) = a\,e^{-at}$. This density has a mean value calculated by the expression $\int_0^\infty a\,t\,e^{-at}dt$. To this we must add the added constant k so that the predicted mean will be $1/a + k$. To find the variance about the mean we calculate $\int_0^\infty a\,t^2 e^{-at}dt - (1/a)^2 = 1/a^2$. In general the expectation of any density is defined as $\int_0^\infty t\,f(t)dt$ while the variance about the mean is defined as $\int_0^\infty t^2\,f(t)dt - (\text{mean})^2$.

Sentence A_r has density $\frac{cb}{c-b}(e^{-bt} \quad e^{-ct})$.

Sentence P_{nr} has density $a\,e^{-at}$.

Sentence P_r has density $\frac{bd}{b-d}(e^{-dt} - e^{-bt})$.

If $P_t = A_{nr}$ then sentence P_t has density $a\,e^{-at}$.

The cumulative form of each density was used in the chi-square analysis presented in Table 3 of the text. For example for any two different time constants x and y we can find the cumulative density of either A_r or P_r by using $1 - F(t) = \frac{1}{y-x}(y\,e^{-xt} - x\,e^{-yt})$, where y is greater than x.

Formulas for the Redundant Check Serial Model

Sentence A_{nr} has density $\frac{ac}{a-c}(e^{-ct} - e^{-at})$.

Sentence A_r has density $\frac{cb}{c-b}(e^{-bt} - e^{-ct})$.

Sentence P_{nr} has density $\frac{ad}{a-d}(e^{-dt} - e^{-at})$.

Sentence P_r has density $\frac{bd}{b-d}(e^{-dt} - e^{-bt})$.

If $P_t = A_{nr}$ then they have the same density.

The cumulative form for any two time constants x and y, where y is greater than x is identical to that presented for the nonredundant serial model above.

Formulas for the Nonredundant Parallel Model

Here we shall develop a more general result than that presented by McGill (1963, p. 347). For a parallel model wherein the first channel to output governs the latency interval, we shall denote the density $f_1(t)$.

Sentence type A_{nr} has density $f_1(t) = (a+c)e^{-(a+c)t}$. This has a cumulative density $1-F_1(t) = e^{-(a+c)t}$.

Sentence P_{nr} has density equal to $(a+d)e^{-(a+d)t}$; while its cumulative density is $1-F_1(t) = e^{-(a+d)t}$.

Sentence A_r has density ce^{-ct} with cumulative density of e^{-ct}.

Sentence P_r has density de^{-dt} with cumulative density of e^{-dt}.

If $P_t = A_{nr}$ then they have the same densities and cumulative functions.

Formulas for the Redundant Check Parallel Model

Since this model requires both channels to have an output before a latency interval is defined we shall denote its density by the subscript '2' as in $f_2(t)$.

Sentence A_{nr} has density $ae^{-at}(1 - e^{-ct}) + ce^{-ct}(1 - e^{-at})$.

Sentence A_r has density $be^{-bt}(1 - e^{-ct}) + ce^{-ct}(1 - e^{-bt})$.

Sentence P_{nr} has density $ae^{-at}(1 - e^{-dt}) + de^{-dt}(1 - e^{-at})$.

Sentence P_r has density $be^{-bt}(1 - e^{-dt}) + de^{-dt}(1 - e^{-bt})$.

If $P_t = A_{nr}$ then they both have the same densities.

The general formula for determining the cumulative density for any two time constants x and y is given by the following expression:

$$1 - F_2(t) = e^{-xt} + e^{-yt} - e^{-(x+y)t}.$$