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Dissociation of Algorithmic and Heuristic Processes in Language Comprehension: Evidence from Aphasia

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Three groups of aphasic patients, Broca's, Conduction, and Wernicke's, and a nonaphasic patients control group were tested for comprehension of object-relative center-embedded sentences. The sentences were of three types: sentences in which semantic constraints between words allowed the subjects to assign a correct semantic reading of the sentence without decoding the syntax, sentences in which semantic constraints were relaxed and for which a correct reading was only possible with knowledge of syntactic relationships among words, and sentences which described highly improbable events. The subjects' task was to choose which of two pictures captured the meaning expressed in the sentence. Broca's and Conduction aphasics performed near perfectly on sentences where they could use semantic information. Their performance dropped to chance when they had to use syntactic information. These results support a neuropsychological dissociation of heuristic and algorithmic processes based primarily, though not exclusively, on semantic and syntactic information, respectively.

Reichenbach (1947), in discussing the relation of logic to analysis of thought, has commented that the study of logic is not actually the study of thought processes, but rather of their "rational reconstruction." That is, a clear distinction obtains between the sequence of psychological processes that constitute thought and the construction of a logic that reflects human thought. The same argument can be applied to the relation of linguistic theory to language use. But, whatever the distance of linguistic rules from psychological processes, insofar as linguistic theory correctly reconstructs the structure of human language it contributes critically to the psychological investigation of language: It specifies structural descriptions

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that language users appear to capture in their encoding and decoding of utterances, and it provides an axiomatic representation or rational reconstruction of the procedures that lead to such encoding and decoding.

Yet, even granting the notion that language knowledge and use may rest with some mental equivalent of a linguistic grammar, i.e., with an algorithm, real-time comprehension also seems to rely on nonformal heuristic systems of a visibly inductive nature. And sorting out the relation between these systems in the normal adult speaker has proved vexingly difficult. In this paper, therefore, we turn to the comparative data from the aphasias in order to pry apart a specifically linguistic competence from a general heuristic capacity to comprehend language purely by means of inductive systems. Our data have been gained from three clinically different types of aphasia: Broca's, Conduction, and Wernicke's (Goodglass & Kaplan, 1972). Broca's aphasia is a common anterior aphasia resulting from a lesion involving the third frontal convolution of the left hemisphere. Patients in this category speak effortfully; show distorted articulation; and most strikingly, produce a telegrammatic output in which syntax is restricted to simple declarative forms; articles and copula forms appear only infrequently, and verbs are most often uninflected. Of great importance, however, is that many such patients seem to know what they want to say and show relatively intact comprehension. Conduction aphasics also show good auditory comprehension, but their spontaneous speech is unlike that of the Broca's. Although often restricted to brief bursts of speech, within these bursts the patients produce well-articulated sequences and a variety of syntactic patterns. An intriguing feature of this syndrome—which is considered to result from a posterior lesion involving the arcuate fasciculus—is that repetition is disproportionately impaired in relation to output and comprehension.

The third group we shall be considering in this report is composed of patients presenting Wernicke's aphasia, a syndrome usually associated with a lesion in the posterior region of the first temporal gyrus of the left hemisphere. One critical feature of this syndrome is impaired comprehension; a second is paragrammatic speech. This latter feature refers to an output marked by facility in articulation and by many long runs of words in a variety of grammatical constructions. But the output is informationally empty—indefinite noun phrases are often substituted for an appropriate noun and when a noun with a specific reference is chosen it is often the wrong one.

Aphasia: Performance versus Competence Breakdown

Of the aphasias described above, the Broca's type appears to offer one of the more interesting theoretical possibilities, pointing, at first glance, to a neurological dissociation between competence and performance—sparing the former, disrupting the latter (Weigl & Bierwisch, 1970; Locke, Caplan, & Kellar, 1973; Lenneberg, 1973). Indeed, accepting that anterior damage spares the patient's tacit knowledge of his language, one current version (Lenneberg, 1973) attributes the telegrammatic output to a neuromuscular problem: The strain of speaking is so great that the patient speaks asyntactically in order to economize effort.

At the level of clinical impression, it is an entirely reasonable assumption. Invoking what might be termed a sufficiency principle, that language competence is at least equal to a patient's best level of performance, and granting the agrammatic patient's near normal comprehension, the patient does seem to retain his knowledge of language. Yet, several recent analyses of the Broca's metalinguistic performance cast doubt on this notion (Zurif, Caramazza, & Myerson, 1972; Zurif & Caramazza, 1975; Zurif, Green, Caramazza, & Goodenough, in press). In fact, the evidence from these studies suggests that the Broca's tacit knowledge of his language is limited in precisely the same manner as is his production.

The metalinguistic data in these latter studies were gained by asking patients with agrammatic speech and control patients with no neurological impairment to judge how words in a written sentence "went best together" in that sentence. The patients indicated their judgments simply by pointing to the words thay they felt clustered best within the sentence. These judgment-derived word groupings served as input matrices for a clustering procedure (Johnson, 1967) that generated, for each sentence separately, a graphic description in the form of a phrase structure tree. The more often any two words of a sentence were judged to form a "constituent," the more compact was the node joining these two words.

Both the Broca's aphasics and the control patients were observed to carry out their judgments on the basis of an implicit hierarchical organization, but the subjective hierarchies of these two groups were notably different from each other. The grouping or relatedness judgments of the control subjects took into account the surface structure restrictions of the sentences, such as using articles appropriately to mark noun phrases. The aphasic patients, in contrast, acted upon the sentences by coupling the content words together. As a result, their judgments violated the linguistic unity of the noun phrases of the sentences (provided by the structure-making determiners) and also failed to account appropriately for copula forms.

It must be emphasized, however, that the aphasic patients did not adopt the strategy of simply disregarding the functors. Rather, they would cluster the functors inappropriately—in a paradigmatic fashion such as grouping two articles in a sentence together, or in a completely unprincipled manner such as grouping an article with a verb. Thus, although Broca's aphasics seemed to acknowledge the basic relations of actor–action–object in their

TABLE 1

SENTENCE MATERIAL USED IN THE EXPERIMENT

A. Control sentences	C. Reversible center-embedded sentences
1. The girl is kicking a green ball.	17. The cow that the monkey is scaring is yellow.
2. The cat is chasing a blue bird.	18. The horse that the bear is kicking is brown.
3. The girl is pulling a red wagon.	19. The cat that the dog is biting is black.
4. The man is reading a yellow book.	20. The fish that the frog is biting is green.
5. The boy is riding a new bicycle.	21. The lion that the tiger is chasing is fat.
6. The girl is holding a broken doll.	22. The girl that the boy is hitting is tall.
7. The boy is throwing a round ball.	23. The man that the woman is hugging is happy.
8. The boy is carrying a sharp pencil.	24. The girl that the boy is tickling is happy.
B. Center-embedded sentences with semantic constraints	D. Improbable center-embedded sentences
9. The apple that the boy is eating is red.	25. The horse that the girl is kicking is brown.
10. The wagon that the horse is pulling is green.	26. The lion that the baby is scaring is yellow.
11. The book that the girl is reading is yellow.	27. The bird that the worm is eating is blue.
12. The bat that the boy is carrying is brown.	28. The dog that the man is biting is black.
13. The bicycle that the boy is holding is broken.	29. The man that the horse is riding is fat.
14. The coat that the girl is wearing is new.	30. The woman that the boy is spanking is sad.
15. The dress that the woman is washing is torn.	31. The policeman that the robber is chasing is skinny.
16. The balloon that the clown is holding is round.	32. The girl that the cat is patting is small.

word groupings, they seemed unable to mark the boundaries of the constituents entering these relations.

Heuristic and Algorithmic Procedures

The above data show that linguistic competence is undermined by anterior brain damage—specifically, that Broca's aphasics no longer fully control algorithmic procedures likely to operate independently from semantic content. Yet, the clinical picture is that comprehension in Broca's aphasia is most often relatively intact. There is some conflict, therefore, as to whether a grammar—any device to assign correct structural descriptions [e.g., cf. Kaplan (1972) & Fodor, Bever, & Garrett (1974)]—is necessary to language comprehension. Phrased as a question: Can heuristics based on sequential regularities and semantic plausibility build meaning representations directly? Or, do they simply serve to reduce the search space of the application of grammatical rules? It was with these questions in mind that the present study was undertaken. Specifically, the issue we addressed was which, if any, of the three types of aphasics—Broca's, Conduction, and Wernicke's—have retained the capacity to use algorithmic procedures in the comprehension of language?

MATERIALS AND METHOD

This investigation made use of a sentence–picture matching task. The processes required for comprehension were inferred from performance levels on the comprehension of sentences that varied in terms of how critical the processing of syntax was in order to respond correctly.

Sentence Material

There were four types of sentences used: three types of center-embedded object relative constructions and a set of control sentences (see Table 1).

Type 1 center-embedded sentences were *nonreversible* (CE_S). That is, sentences of this type contained certain semantic constraints that did not permit the alternative pairing of noun phrases (NP) and verb phrases (VP). Consider in this respect, *The apple that the boy is eating is red*. Clearly, in this sentence it must be the boy that is doing the eating and not the apple, and, furthermore, it is the apple that is red. Thus the first NP must be paired with the second VP.

Type 2 sentences were *reversible* center-embedded sentences (CE_R). In these sentences certain semantic constraints were relaxed and a correct interpretation depended on a knowledge of syntactic regularities of the language. An example of this sentence type is: *The boy that the girl is chasing is tall*. In this case both the boy and the girl can do the chasing and both can be tall. A correct interpretation of this sentence requires that a correct pairing be made between girl and chase and boy and is tall. Note that this sentence is not structurally ambiguous. Native speakers of English will assign only one meaning to this sentence.

Sentences of the third type were *improbable* (CE_I). That is, they were well formed grammatically, but they violated the speakers "knowledge of the world." An example of such sentences is: *The boy that the dog is patting is fat*. This sentence violates neither syntactic nor semantic rules of English. Yet it is clearly deviant from a point of view of our knowledge of the world. It is usually boys that pat dogs and not vice-versa. It remains the case, however, that adult speakers of the language can assign a correct interpretation to sentences of this type.

The fourth type of sentences were *control sentences* (C) of the form, *The boy is eating a red apple*. These sentences, like the CE sentences, have two underlying sentoids. In the example given above they would be: (1) *The boy is eating an apple*; and (2) *The apple is red*. Of course, the deep structure of the control and CE sentences are not necessarily the same.

Picture Materials

The experiment centered on a sentence–picture matching task. And if we assume that a correct choice can be made on the basis of partial information, the nature of the distractor (incorrect) item becomes critical. This can be illustrated by an analysis of the sentence material used in the present research.

Consider the sentence, *The cat that the dog is chasing is brown*, in terms of its underlying propositions: (1) The dog is chasing a cat; and (2) the cat is brown.

A correct pictorial representation of this sentence must depict both propositions correctly. Now, it is obvious that a distractor can depict a change in either or both of these two propositions, making the whole picture an incorrect referent of the sentence. Thus, for example, by focusing upon only one of the propositions we can show a picture of a dog chasing a black cat rather than a brown one.

Of the many possible distractor types that could have been constructed for each sentence, we chose the following four: (1) a change in the complement (predicate adjective) of the matrix sentence, (2) an incorrect depiction of the main verb, (3) an incorrect depiction of both the main verb and the complement, and (4) a picutre showing a reversal of matrix sentence subject noun (N_1) with embedded sentence subject noun (N_2). As an example of these contrasts for the sentence, *The cat that the dog is chasing is brown*. The four incorrect alternatives were:

(1) A dog chasing a *black* cat.
(2) A dog *biting* a brown cat.
(3) A dog *biting* a *black* cat.
(4) A *cat* chasing a brown *dog*.

On any one trial the correct pictorial representation of the auditorily presented sentence was paired with *one* of the four incorrect pictorial representations. The subject's task was to choose from the pair of pictures the one that represented the cognitive content of the spoken sentence. It is quite obvious that the subject's choice need not have depended on his full

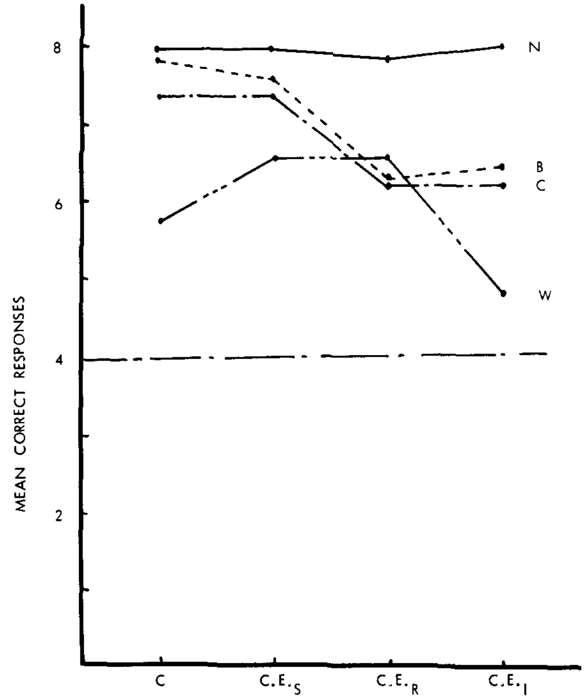

FIG. 1. Mean correct performance for each patient group (N = Normal, B = Broca, C = Conduction, and W = Wernicke) as a function of sentence type (CE_S = semantically constrained, CE_R = reversible, CE_I = improbable, and C = control).

understanding of the spoken sentence. Thus, for example, in the complement change condition (Condition 1) all the subject needs to know to correctly choose a match to the spoken sentence is that the cat is brown, not *black*. In other words, the subject could give the correct response on the basis of partial information. It is also apparent that the four distractor-type conditions require different levels of understanding in order for subjects to respond correctly. The important aspect to note here is the difference between the "reversal of N_1 with N_2" and the other three incorrect alternatives which feature lexical changes. The pictures that represent changes 1, 2, and 3 retain the syntactic relationship that obtains between the matrix sentence and the embedded sentence. The locus of change for 4, however, is to be found in the syntactic relationship between the two underlying sentences. Thus, a proper test of syntactic understanding is possible only in the fourth picture-contrast condition.

Subjects

The aphasic patients included in this study were classified on the basis of clinical examination and, with the exception of one conduction aphasic, on the results of the Boston Diagnostic Aphasia Test (Goodglass & Kaplan, 1972). Where possible, laboratory data (brain scan and EEG) provided supporting evidence for lesion localization. There were five Broca's aphasic patients, five Conduction aphasics, and five patients presenting Wernicke's aphasia. All but two of these patients, one Broca's aphasic and one Wernicke's, had cerebro-vascular accidents; the two exceptions had sustained a traumatic injury to the head. All were male, and only four patients, one Wernicke's, one Broca's, and two Conduction aphasics, had been educated beyond the high school level. It should be noted, however, that these differences in educational background did not result in performance differences among patients within groups. Their ages ranged from 29 to 79 years with an overall mean age of 54.

Five male patients chosen from the nonneurological wards of the Boston Veterans Administration Hospital served as control subjects. These patients were comparable in age and educational background to the aphasic patients.

Testing Procedure

Each subject was tested singly in a quiet room. Before testing began each subject was screened to ensure that he understood the general testing requirements. Each subject received a different random order of the 32 test sentences: two sentences for each combination of the four sentence types (semantically constrained, reversible, improbable, and control) and the four distractor types (complement, main verb, main verb and complement, and subject–object reversal). The experimenter read each sentence in a clear voice at a conversational pace (pauses before and after the embedded clause were not especially emphasized), and the subject was required to indicate his choice of the picture that captured the meaning of the sentence. The subject's response could be either verbal or simply a pointing gesture. Each response was recorded immediately.

Design

A three factor with two repeated measures design was used in this experiment. The between factor (four levels) was subject group: three aphasic groups and a nonneurological control. The two repeated measure factors were sentence type and distractor type. Each of these two factors had four levels as described above.

RESULTS

The results relevant to our contention that brain damage may independently affect algorithmic and heuristic processes are the double interaction of sentence type and patient group, and, more clearly, the triple interaction of sentence type, distractor type, and patient group. The sentence type by patient group interaction was significant, $F(9,48) = 2.64$, $p < .025$. Figure 1 presents the details of this interaction, showing mean correct performance for each group of aphasics and the control group as a function of sentence type. There are a number of important points to be noted in this figure. First, when semantic constraints were absent, as in CE_R and CE_I sentences, performance for the Conduction and the Broca's aphasics dropped substantially. This suggests that both Broca's and Conduction aphasics are impaired in their capacity to algorithmically compute a full structural description of the CE sentences. A second point of interest to the finding that the Conduction aphasics performed in a very similar manner to the Broca's is that, alongside the repetition deficit in conduction aphasia, there is an additional disruption to mechanisms of comprehension. Finally, while it is of interest to note that the Wernicke's performed very differently from the other aphasic groups, we remain

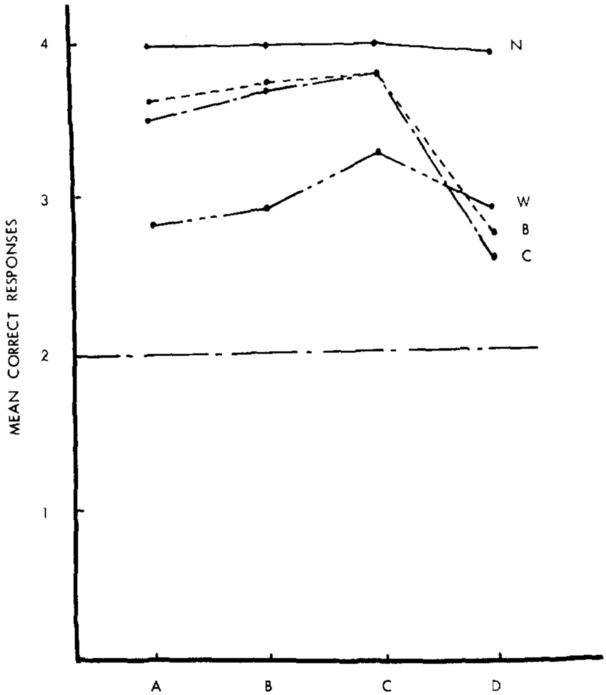

FIG. 2. Mean correct performance for each patient group (N = Normal, B = Broca, C = Conduction, and W = Wernicke) as a function of distractor types (A = predicate adjective change, B = main verb change, C = predicate adjective and main verb change, and D = subject–object reversal).

perplexed about the actual pattern of their performance: Their general level of performance was quite high, but they seemed insensitive to either the syntactic (C vs CE) or the semantic (CE_S vs CE_R and CE_I) factors manipulated in the experiment. (The good level of performance in the Wernicke's patient may have been due simply to a bias in the selection of patients; since patients had to have enough comprehension skills to be able to understand our instructions and perform the experimental task, we likely included only very mildly impaired, atypical Wernicke's aphasics.)

Figure 2 shows mean correct responses for the groups as a function of distractor types. The interaction is significant, $F(9,48) = 2.50, p < .025$. As can be seen in this figure, Broca's and Conduction aphasic patients performed quite accurately on distractor types which cued only lexical changes (83 to 92%). However, when the distractor type marked a syntactic change, performance over all sentence types dropped to about 68%. This provides further evidence for the notion that neither the Broca's nor the Conduction aphasics have retained syntactic algorithmic processes. Clearly, then, these two patient groups were relying on partial cues to

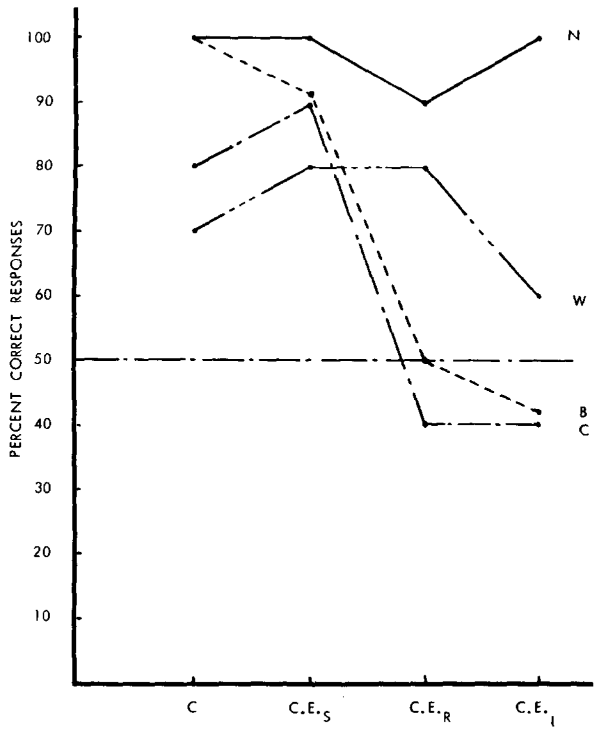

FIG. 3. Mean correct performance for each patient group (N = Normal, B = Broca, C = Conduction, and W = Wernicke) as a function of sentence type (CE_S = semantically constrained, CE_R = reversible, CE_I = improbable and C = control) for the subject–object reversal distractor type only.

make the correct choice: When they had to rely on syntax, their performance was impaired considerably.

Consequently, a fair assessment of their comprehension skills, at least with respect to their ability to use algorithmic processes, can only be obtained by considering their performance on sentence types for the reversed N_1/N_2 distractor type condition. Figure 3 depicts these data. Again, the conclusion is inescapable—Broca's and Conduction aphasics do not seem at all capable of using algorithmic processes. Thus, for those sentences that were semantically constrained, performance was approximately at the 90% level, but it dropped to chance level when these semantic constraints were not available. As for the Wernicke's, their pattern of performance again remains uninterpretable.

DISCUSSION

It appears that the presumed dissociation between language production and comprehension does not hold for Broca's and Conduction aphasics:

The present analysis of their comprehension skills suggests that such patients are as impaired in comprehension as they are in production. The impairment, moreover, is a specific one—they are unable to use syntactic-like algorithmic processes. Yet, of equal importance, they have retained the capacity to use heuristic procedures to assign a semantic interpretation to, at best, an incompletely represented syntactic organization. From the evidence at hand, these heuristics are based upon the semantic plausibility of the arrangement of lexical items (CE_S vs CE_R sentences) and upon a sequential regularity whereby noun–verb surface arrangements can be mapped as actor–action relations (control sentences). These results have clear implications for both neurolinguistic and normal language processing theories.

With respect to neurolinguistic theories, the results are contrary to the view that Broca's aphasics have retained a normal tacit knowledge of their language. The present data together with the previously reported metalinguistic data (Zurif & Caramazza, 1975) suggest that, at least for the Broca's aphasics, brain damage affects a general language processing mechanism that subserves the syntactic component of both comprehension and production. The implication that follows is that the anterior language area of the brain is necessary for syntactic-like cognitive operations.

Conduction aphasics also were incapable of using syntactic algorithmic processes [see also Saffran & Marin (in press) and Scholes (in press)]. The question arises, therefore, as to whether syntactic operations also rely on cortical regions posterior to Broca's area or whether the conduction deficit should be considered within a disconnection framework, that is, as the severing of a connection to Broca's area (Geshwind, 1970). Given the impressive arguments offered by Geshwind, we are presently satisfied in treating it as a problem of disconnection, but a disconnection from an area that subserves sytactic processes.

As already mentioned, there is very little to be gained from the Wernicke's performance in the present study. We can only surmise that because we chose subjects who could understand our instructions we inadvertently selected patients who had recovered sufficiently to perform above chance with the aid of "unstructured" strategies.

The results we have reported also bear on questions of normal language processing. A central issue in psycholinguistics in the past decade has centered about the role of a fully deterministic procedure (a grammar) in sentence comprehension. Specifically, a major concern has been how a grammar interacts with other cognitive processes in the act of comprehension. Though there has been considerable discussion of this issue, the area is conspicuous for the paucity of empirical evidence relating to the problem. Nonetheless, a general consensus seems to be that language comprehension results from the application of both algorithmic and heuristic processes. Recently, Fodor, Bever, and Garrett (1974), in their review of the literature, discuss several possibilities concerning the relation of heuristic and algorithmic processes in language comprehension. Two of these possibilities are: (1) Algorithmic processes serve only as backup mechanisms, just in case the heuristic processes *do not* obtain a solution; and (2) Both heuristic and algorithmic processes are involved in comprehension, but the heuristic processes function only to restrict the search space of a grammar. Of these two possibilities, the neurological dissociation between heuristic and algorithmic processes, as shown by the performance of the Broca's and Conduction aphasics, clearly favors the first one: namely, that heuristic and algorithmic processes can independently assign semantic interpretations to utterances. As a corollary, this evidence also highlights the role of an algorithmic, deterministic procedure in sentence comprehension; specifically, for those instances where the input is insufficiently constrained for the efficient use of heuristic procedures.

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