COMPUTATIONAL NEUROLINGUISTICS - WHAT IS IT ALL ABOUT?*

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ABSTRACT

Computational Neurolinguisties (CN) integrates artificial intelligence (AI) methods with concepts of neurally motivated processing to develop cognitive models of natural language processing.

HOPE is one example of a model developed to address issues in CN. The model is parallel, and exemplifies language as the result of <u>time synchronized</u> processes which are asynchronous in nature. Furthermore, the model is substantially validated to include normal behavioral evidence in its design. In addition, it attends to aspects of language breakdown which are well documented in the literature of neurolinguistics or aphasia.

This paper discusses assumptions which underlie the CN approach to model development. It will describe the neurally motivated or "natural computational" processes which produce the model's observable and verifiable behavioral results. The differences in the CN approach to other models of parallel memory process and behavior will be presented. Finally, the contribution of the CN research approach as a tool for investigating the breakdown of language performance and its potential contribution to understanding brain function will be discussed.

1. INTRODUCTION

Computational Neurolinguistics (CN) was first described by Arbib and Caplan (1979) as a possible approach to enhancing studies of aphasia by employing a HEARSAY-like, interactive processing paradigm to model aspects of aphasic language performance.

The HOPE system (Gigley, 1981; 1982a; 1982b; 1982c; 1983a) encompasses a proposed solution to the issues raised by Arbib and Caplan (1979). CN, as a research approach has evolved during HOPE'S development to include many issues which were not obvious in that first discussion. HOPE represents an approach to cognitive modelling which attempts to develop computational models of process that are behaviorally relevant on two levels—

(1) at the neural processing level, where the encoded processing mechanisms are based on current evidence of neural process, and

(2) at the natural language behavioral level, where the results of the observable computations of the model and its final result states are verifiable with respect to human language performance, both normal and pathological.

The development of CN models emphasizes process. A primary assumption of this approach, which is not an assumption for much of AI, is that much is gained by including neural-like computations in models which attempt to "simulate" any cognitive behavior.

Furthermore, the assumption that time is a critical factor in neural processing mechanisms and that it can be a significant factor in language behavior in its degraded or "lesioned" state can only be studied within a computational paradigm as provided in CN models. The complexity of the computation that arises in defining the time-coordination of parallel interactive processes under both a "normal" state and in the "lesioned" condition requires an implemented model to keep track of the process.

The CN methodology as it has developed during design and implementation of a first example of such a model, will first be presented within the scope of its goals in defining such models. Then, the working implementation of that model, HOPE will be briefly described to demonstrate the relevance of the approach and how it meets the simultation criteria at the neural process or natural computation level, as well as at the natural language performance level. The CN approach will be briefly compared to other neurally motivated processing models of aspects of sentence comprehension such as the connectionist models (Feldman, 1981; Cottrell and Small, 1983), the parallel interpretation model of Waltz and Pollack (1985), and the perceptual processing models of Anderson, Silverstein, Ritz, and Jones (1977), McClelland and Rumelhart (1981), Wood (1978) and Gordon (1982), to illustrate how the present implementation differs from each.

Finally, the potential use of CN models as investigative tools will be described to illustrate the most obvious practical application of the research and the potential contribution of the research to understanding brain function.

2. ASSUMPTIONS UNDERLYING THE CN APPROACH TO NATURAL LANGUAGE PROCESSING

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One goal in approaching the study of natural language processing as it can be computed within a neural-like processing paradigm is to obtain a better understanding of how brain function can subserve language behavior.

The first constraint on the design of such models is the neural-like control paradigm. Because of its adoption, with the associated internalized control of the process, the problem decomposition is different than in the development of serial-order models of language processing such as are usually found in linguistic theory and other AI approaches to language processing.

Developing a CN model requires that evidence from errorful language performance provide critical clues that are used to define the interactions among the defined representations. This data is available in the behavioral literature such as that of slips of the tongue, the literature of neurolinguistics and even in the descriptions of the effects of brain stimulation on language performance.

The critical emphasis in the CN approach is that language behavior is defined within both the "normal" state and within the "lesioned" condition using evidence from psycholingustic studies and neurolinguistic studies of aphasia. When there is insufficient evidence within the literature, linguistic theory provides the basis for design decisions which are consistent with the processing paradigm. The role of the grammar in the approach is presented in Gigley (1985) and will not be further described here. What should be noted is that all representations that are independently specifiable in the model find support in the literature mentioned above. This is documented in Gigley (1982b) and will not be repeated here.

The primary use of the model in its simulation state is to determine what the effects of specifiable, interpretable processing "1esions" are on the overt behavior of the model and whether the performance finds any clinical support.

2.1 An Overview of the Neural Processes in HOPE'S Design

HOPE is a neurolinguistically constrained processing model of natural language comprehension. It is implemented at the single sentence comprehension level. Although there is substantial evidence that comprehension occurs within context, the test paradigm most often used in studying aphasic patients comprehension abilities is within a task that precludes any preset context. For this reason, the single sentence level was considered sufficient in the first level implementation.

Neural-like representations and functions that are encoded in the processing paradigm and that effect the control include:

(1) nodes interpreted as representations of information that are threshold mechanisms, and are ambiguous in their interpretation,

(2) automatic meaning access that includes a fixed-time spreading activation scheme,

(3) an automatic decay scheme that affects all active information if it does not receive any subsequent input or change state, and

(4) node state changes that are automatic and related to the threshold firing of a node.

Models of neural-based computations that existed prior to the development of HOPE discussed some of these aspects of neural behavior and applied them to psychologically defined models (Baron, 1974a; 1974b; Cunningham and Gray, 1974), or applied a systems analytic approach to the analysis of aphasic behavior (Lavorel, 1982; Lecours and Lhermitte, 1969; Marcus, 1982). However, in the case of the latter models, they do not meet the requirement of the CN approach that neither redesign nor reprogramming be requisite to defining "lesion" performance of the model.

2.2 Behavioral Constraints Underlying HOPE'S Design

As briefly mentioned above, the representations that are included in the design of CN models are required to be supported by adequate evidence. Evidence from the psycholinguistic and neurolinguistic literature supported the inclusion of knowledge structures that represent a PHONETIC representation, a representation of morphological relationships, case-control information for verbs, a representation of a GRAMMAR, word-meaning representations and a contextually determined memory representation that is distinct from world knowledge called a PRAGMATIC representation.

Additional behaviorally motivated constraints were included in the design of HOPE to provide a parameterized processing ability to satisfy the "lesionability" criterion of the CN approach. Specific "lesion" conditions that are possible within the design are not claimed to be the only relevant lesion conditions that need study. Those included are based on clinical observation and hypothesized causes of the observed language degradations in the aphasic populations.

One hypothesized cause of performance degradation available in HOPE and in no other approaches is that time-coordination of serial-order processing is a critical part of the neural processing mechanims"of brain function and may be affected under "lesion" conditions. Its inclusion is further supported by clinical studies that indicate that the time course of input presentation to aphasic patients affects their processing ability (Brookshire, 1971; Laskey, Weidner, and Johnson, 1976). Prior to HOPE'S definition, there was no suitable way to include such a dynamic factor as a suggested cause of the behavior deficit.

Other specific clinically defined "lesion" conditions addressed in the design Include:

(1) degradation of knowledge representations within the different structures,

(2) inability to access knowledge representations, and

(3) short-term memory capacity problems.

Having presented HOPE as an example of one model which meets the behavioral and processing criterion of the CN approach, the next sections will describe the serial-order processing computations and how they effectively compute in a "natural" sense to produce results which can be compared with normal and pathological language behavior.

3. FOCUS ON PROCESS

This section will describe what the serial order processes included in HOPE'S design represent. For complete detail of the model with examples of simulations in both "normal" and "lesion" states, the interested reader is referred to Gigley (1982a; 1982b; 1983a). Furthermore, as the processes are defined at a meta-level in HOPE, the implementation permits definition of a set of specific instantiated models within the overall processing paradigm. It is due to the meta-level implementation of the neural processing algorithms, that the resultant model is more general in its overall processing paradigm than the paradigm that 1s found in other parallel approaches to cognitive modelling. This will be further elaborated in the subsequent section.

HOPE stresses the process of natural language by incorporating a neurally plausible control that is internal to the processing mechanism. There is no external process that decides which path or process to execute next based on the current state of the solution space. It is a time-locked process. At each process time interval, six types of serial-order computations occur. Each of these computations can be interpreted to represent an aspect of "natural computation" (Lavorel and Gigley, 1984).

Information in HOPE is encoded at a phonological level as phonetic representations of words (a stub for a similar interactive process underlying word recognition), at a word meaning level as multiple representations each of which has a designated syntactic category type and orthographic spelling associate to represent the word's meaning (also a stub), within a grammar, and as a pragmatic interpretation.

Each piece of information is a thresholding device with memory. It has an activity value, initially at a resting state, that is modified over time depending on the input. Interconnections are of two types. Associational interconnections permit multiple interpretations for any active information in the process. Using this concept, an active node can represent information that is shared among many interpretations. Other interconnections are defined across representational levels and are asynchronously traversed. They are not defined between specific instances of the encoded representations, but are defined to affect any information within a specific level of representation. (Cf Gigley and Boulicant, 1985 for an elaboration of the Inherent ambiguity in the representation and its role 1n cognitive modelling.) There 1s an automatic activity decay scheme whose magnitude is affected by the state of the information, whether it has reached threshold and fired or not.

Activity is propagated in a fixed sense to all aspects of the meaning of words that are "connected" by spreading activation (Collins and Loftus, 1975; Fahlman, 1981; Hinton, 1981; Quillian 1968/1980). Simultaneously, information interacts asynchronously due to threshold firing. This is achieved by the time-coordination of six serial order processes. The exact serial-order processes that occur at any time-slice of the process depend on the "current state" of the global information; they are context dependent.

The independent serial-order processes "computed" at each update include:

(1) NEW-WORD-RECOGNITION: Introduction of the next phonetically recognized word in the sentence.

(2) MEANING-PROPAGATION: Fixed-time spreading activation to the distributed parts of recognized words' meanings.

(3) DECAY: Automatic memory decay exponentially reduces the activity of all active information that does not receive additional input. It is an important part of the neural processes that occur during memory processing.

(4) FIRING-INFORMATION-PROPAGATION: Asynchronous activation propagation that occurs when information reaches threshold and fires. It can be INHIBITORY and EXCITATORY in its effect. INTERPRETATION is a result of activation of a pragmatic representation of a disambiguated word meaning.

(5) REFRACTORY-STATE-ACTIVATION: An automatic change o? state that occurs after active information has reached threshold and fired. In this state, the information can not affect or be affected by other information in the system.

(6) POST-REFRACTORY-STATE-ACTIVATION: An automatic change of state which all fired information enters after it has existed in the REFRACTORY-STATE. The decay rate is different than before firing, although still exponential.

The computations are defined over the representation types: PHONETIC, PH0N-CAT-MEAN, GRAMMAR and PRAGMATIC. Each is referred to in the HOPE representation as a space. Algorithmically, the above processes are computed in order and applied to all active information at time, t-1, to produce a current state at time, t.

FIRING-PROPAGATION requires different procedures for each representation type. Firing can excite and inhibit other types of representations in both a bottom-up and top-down manner. It occurs asynchronously as a result of "accumulated" activity. This is in contrast to the fixed-time spreading activation which occurs across the "meaning representations" due to the lexical access. These processes are mutually affective.

Figure 1 contains snapshots of three consecutive intervals during the "normal" simulation run for the sentence, "The boys ran." It illustrates how different "actual" computations can occur with these processes depending on the context of the information.

The state of the "global" representation at

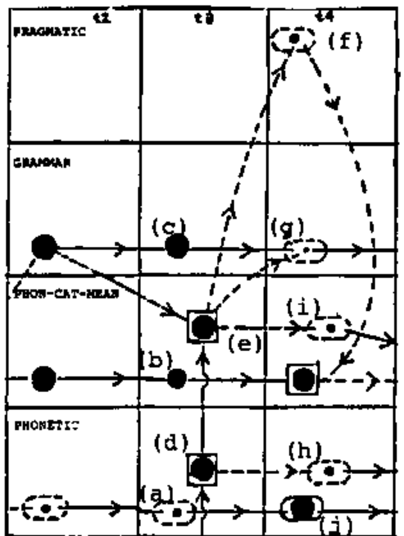

Figure 1: Example Serial Computations

time t-1 determines the exact instantiations of information which are affected during the processes. The effect is shown at time t. Time intervals, t3 and t4 will be discussed in the context of the relevant computations which occur and result in the states represented in t4.

Parenthesized labels within the text refer to Figure 1. The Figure is a variation of one found in Gigley (1983a) where a more detailed explanation of the dynamics of the simulations is provided. The actual implemented algorithm is presented in Gigley (1982a; 1982b).

In Figure 1, the size of the circles or nodes represents the relative activity value of the information; larger means more active. The threshold value is a user defined parameter. Any information in the Figure that is at threshold is indicated as . The REFRACTORY state is denoted , while the POST-REFRACTORY state is denoted . The lengths of time (number of intervals) for each state and for automatic decay are user parameters, set at 2. Information "knows" its own state. Changes of state and decay computations occur when the information "knows" that they should. To achieve this, all information includes time interval counters, its activity value, and its appropriate rate of decay.

Each of the above listed independent computations are applied at time interval, t-1. Any results that arrive simultaneously are summed, except for NEWWORD introduction which presently initializes all meanings for a word as if it were the word's first occurrence in the sentence, even though it may not be.

The context at t3:

The state at t3 contains previously computed states from t2 as follows: the word, "the," is in the REFRACTORY state in the PHONETIC space (a). Its meaning, shown in PHON-CAT-MEAN has just decayed (b). The grammatical aspect of the meaning of the determiner, "the," the noun prediction is shown at its initial activity level in GRAMMAR (c). It is ready to decay because of length of time without input.

Computations at t3:

1) NEWWORD introduction: second word of sentence, "boys" enters PHONETIC (d).
2) Spreading activation of meaning(s): one meaning for boys activated at a subthreshold value.
   Spreading activation from GRAMMAR: All noun meanings are excited from t2. Noun meaning for "boys" is at threshold (e) in PHON-CAT-MEAN.
3) Nothing is ready to DECAY: None computed.
4) FIRE all information at threshold: PHONETIC representation of boys (d) and disambiguated meaning (e) in PHON-CAT-MEAN, produces noun INTERPRETATION (f) at t4 and inhibitory feedback (g) in GRAMMAR.
5) FIRING change of state: Firing information, (d) and (e) change to REFRACTORY state (h) and (i), respectively.
6) REFRACTORY change of state: PHONETIC representation of "the" in REFRACTORY STATE (a) is ready to enter POST-REFRACTORY state (j) in t4.

This example illustrates how the design of HOPE differs from the other models especially in the "meta-level" specification of the computations, which depend on the interconnections of the information to be fully specified. As the affects of the processes are context dependent, there is a variability in the performance that does not occur in other neurally motivated approaches to language behavior.

Due to the various combinations of computations which can occur, simulations of the model often produce surprising, but behaviorally interpretable results. One example which occurred during a "lesion" simulation of slowed propagation for the sentence "The boy saw the buildings." is: "saw" is interpreted as a noun and "building," as the verb of the sentence. A possible interpretation relating a saw with building is suggested for the "simulated patient." While plausible, this is unlikely to be included in a clinical study. A contribution of the CN approach may be to provide a mechanism for predicting "possible" foils that provide insights about incorrect processing (Gigley and Duffy, 1982).

During processing, change of state over time as well as the cause of the change can be observed. Analyzing both aspects of the process provides the information that is useful in comparing the "normal" and "lesion" simulations of the model. In this way, the effects of a given "lesion" can suggest hypotheses in a well defined linguistic context. Because each simulation must be run on a complete cover set of sentences that are specified for any specific model, there is a unique hypothesized patient profile defined that can be clinically verified (Gigley, 1982b; 1983a; 1983b). A cover set of sentences is the mathematical cover of all valid syntactic sentences possible for the defined model.

The next section will briefly describe other neurally based processing approaches to cognitive modelling at several levels to illustrate how HOPE differs from each. The chief difference is in the inclusion of "lesionability" as a dynamic aspect of the processing definition in the CN approach which is not present in any of the other model designs.

4. PARALLEL MODELS OF BEHAVIOR

Recently, the concepts of neural processing have been incorporated into AI models of cognitive process. Models which incorporate neural-like processing mechanisms exist at several levels and are mainly intended to model normal behavior. A few have addressed the "lesion"[1] evidence.

4.1 Perceptual Recognition Models

These models represent the earliest attempts to integrate the behavior of neural-like computation devices with observable, verifiable behavior. They all utilize the basic model of Anderson, Silverstein, Ritz, and Jones (1977).

The Anderson, et al model represents a neural-like convergent approach to learning pattern discrimination. The model is comprised of threshold mechanisms which are mutually interconnected. There is a vector of inputs, each of which is transmitted using weights to each of the cells which make up the recognition device. Given a suitable training set of inputs, the interconnection vectors of weights can be suitably tuned to produce pattern discrimination of input patterns, even under noisy conditions.

"Lesion" experiments on versions of this model have been studied and interpreted with respect to understanding phonemic misperceptions by aphasic patients (Wood, 1978) and for anomia (Gordon, 1982).

4.2 Associative Models of Memory Processing

Two recent models of associative memory processing are relevant to understanding HOPE'S "memory" processing scheme, Fahlman's NETL (1981) and HINTON's model (1981). Both assume spreading activation. However, Fahlman's marker passing schema is able to include information in the activation. HOPE'S spreading activation is more similar to the original Quillian model (1968/1980) and Hinton's (1981) in that only activity is propagated. There is no contained "meaning." Activation can only be interpreted within the global context of the memory in this latter case. This introduces more ambiquity throughout into the process. Memory process is only one aspect of the HOPE model. It plays an important role in the sentence comprehension process.

4.3 Connectionist Approaches to Sentence Processing

One of the most developed approaches to parallel, neurally-movivated process models is the connectionist approach (Feldman, 1981; Cottrell and Small, 1983). This approach concentrates on specifying networks of cells to represent percepts, or concepts, depending on the level of application.

While the CN approach assumes that there are networks of cells to effect the neural-like computations, the explicit definition of such networks is not the goal of the work. There is an emphasis in the CN approach to define processing interconnections at a meta-level, such as between meaning representations and pragmatic interpretations of them; between phonetic representations and the associated meanings. The interconnections in HOPE are defined as suggested from the aphasic literature.

The CN approach does not include mutual inhibitory factors to the extent that the connectionist models do. In connectionism, the inputs to nodes are constrained to act in an OR of AND condition. While the spreading activation schema is similar to that in HOPE and in the CN approach, the use of vector inputs to each node is not. The CN approach assumes that time will affect the computation in a manner that eliminates the need for many of the above connectionist constraints.

Finally, the parallel model of sentence parsing that has recently been developed by Waltz and Pollack assumes similar constraints to the connectionist approach. While the interactions that can be observed during the time-course process of their model are similar to those obtainable in the "normal" process of HOPE, the parallel algorithm is not, as it relies heavily on mutually exclusive connections at different levels of the process.

4.4 A Cognitive Model for Letter Perception in Context

McClelland and Rumelhart (1981) implemented and have validated a parallel model of letter perception in context. Of all the models discussed, their implementation is the closest in design to that of HOPE. There are three main differences. Their input is in parallel, while HOPE input is time sequenced. Secondly, their memory decay, is fixed rate across the computation without change of state. And finally, they include a binary feature detection, mutual inhibition schema, to recognize the input. While this assumption is neurophysiologically supported for perceptual visual processing, it is not for auditory. When one hears a sound such as "ah" what is its binary counterpart — "not ah?". Because of this, in the CN approach, only the recognized input is activated. There is no explicit inhibition of any information at the perceptual level; it is just not activated.

The CN approach assumes that each entity in the model is defined in a local context. There is no built-in knowledge about the global interconnectivity patterns that exist in the model. Therefore, there is no way of explicitly defining the mutual inhibition that is a critical part of the convergence in all of the above mentioned models.

4.5 The HOPE System

The system design in HOPE includes two subsystems. One subsystem allows an experimenter to define the representations that are relevant to the sentence comprehension tasks that are being studied. It permits definition of the appropriate vocabulary, the related grammar, and interpretation functions that define the compositional aspects that occur when words are disambiguated in the course of understanding the sentence.

The second subsystem allows the experimenter to tune the model so that it exhibits "normal" performance. This must be done on a complete cover set of sentences to assure that the baseline performance of the model is intact. After tuning the model, this second subsystem permits the experimenter to simulate lesion conditions by modifying the parameters in interpretable ways to depict a "lesion." As when the model is tuned, each "lesion" simululation must be run on every sentence of the given cover set of sentences to fully define the patient profile for subsequent validation.

4.6 Summarizing the CN Approach

The main aspects of the CN approach to neural control that differ from the above described models and which provide a more general framework for studying natural language processing can be summarized as follows:

(1) CN knowledge representations are ambiguous without assessment in a global context.

(2) Interconnections among representations are implicitly encoded rather than being explicitly defined, as in the connectionist models.

(3) Control is encoded independently of what is specifically represented in any defined model and is defined at a meta-level with respect to the kinds of knowledge representations used.

(4) Model design permits the definition of a set of problem models such that for any explicitly "tuned" control simultation, one can modify the "tuned" parameters in ways that can be interpreted to reflect hypothesized causes of deviation in performnce and observe the results on the control simulation without any necessary redesign or re-implementation.

The next section will assess the contribution of CN models to our understandings of brain function within language processing, especially in regard to hypothesizing behavior degradations under "lesion" conditions.

5. INVESTIGATING BRAIN FUNCTION USING CN

Development of CN models does not assume any direct correlation with explicit physical areas of the human brain. Instead, it provides a dynamic, interactive, parallel processing paradigm in which to formulate hypotheses about degradations in processing ability. Questions raised within the approach concern interactions that can become desynchronized. This can be as much a problem with a process, as elimination of information. However, it is much more difficult to study when there is no means available to trace the dynamics.

The CN approach provides this facility. Researchers can now raise questions concerning the effect that an aspect of processing such as of slowing propagation has on the overall performance. Furthermore, the results which have been produced under such conditions, indicate that behavior that was previously only attributed to a degradation in representation, could be explained by the processing degradation and that furthermore, because the processing degradation is the cause, the observed behavior is not always completely affected. The resultant behavior is variable, but perhaps affects only one type of information.

Under a "lesion" condition of slowed propagation, the model produces the following "patient profile":

The "model" patient should be able to repeat correctly all sentences up to five words in length. The "model" patient recognizes that a complete sentence has been heard, although it often is not understood correctly. Proper nouns are always understood, while referential nouns with an appropriate determiner are not. Sentence comprehension for the "model" patient is sometimes correct. When a sentence contains only proper nouns then there is correct understanding. However, when either noun is a referential noun, the agent or the direct object in the sentences being studied, the comprehension is affected to the extent that a noun interpretation for the intended verb of the sentence occurs. The above result is described and documented in Gigley (1982b; 1983a; 1983b).

The importance of the above profile is that it is mathematically defined and covers an entire set of possible inputs within a computationally well-defined model of performance. Other neurolinguistic studies do not require such explicit definition.

What is hoped in developing models which can exhibit the above qualities is that greater insights can be developed about the role of aspects of processing in the brain and how they work in an integrated fashion to produce cognitive behavior. The HOPE model represents a beginning.

6. WHERE WE ARE AND WHERE ARE WE GOING?

Current work is underway to develop validation techniques to adequately study the results of the model. There are extensive sets of studies which must be done on a single patient populations to provide information on the model's validity. It is hoped that results of such carefully coordinated studies will provide information that will lead to better model definition (Gigley and Duffy, 1982).

Planned system development includes a representation for meaning and assessment of the representations for production under the same processing control as is used in comprehension. In both cases, there is extensive behavioral evidence to assimilate to define sufficient representations with their interconnections. In addition, an initial attempt has been made to specify a model of HOPE for processing French. This has raised some interesting cross-linguistic issues (Gigley, 1984).

The CN approach provides a first attempt to implement models of natural language performance that addresses how language might be processed in a neural mechanism, such as the human brain. It is the first model that integrates behavior evidence at two levels in its design, at the neural-computation level and at the human performance level. Furthermore, CN provides researchers with a facility to consider behavior as the result of a time-dependent, interactive, parallel process that is dynamic and can produce variable results in a manner that is consistent with human performance.

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