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MEASURING THE NEURAL DYNAMICS OF LANGUAGE COMPREHENSION PROCESSES

Abstract. Recordings of electrical activity generated in the brain in response to specific stimuli now provide an important source of information about the temporal and topographical distribution of language processing events in the brain. Many of our theories of language processing are based upon reaction time studies and use the new brain based findings sparingly. One reason for this is that much of the results from brain recordings are seen to be primarily recapitulations of reaction time findings. A new approach to analyzing evoked electroencephalographic data, Contrastive Signal Coherence (CSC) assesses the coherence of the evoked signal using the techniques of non-linear systems analysis. This determination of signal quality, combined with the measure of signal quantity as calculated in the standard voltage averaged approach to Evoked Brain Potentials (ERPs), provides a richer reflection of the dynamic properties of language related brain potentials and significantly enhances our view of cognitive cortical events. In this paper, we present the results of an ERP study in which we combined the traditional voltage averaged analysis and CSC to address two competing accounts of Case ambiguity resolution, a data driven, expectation based account following Schlesewsky (1997) and an information driven Diagnosis and Repair account following Fodor and Inoue (1994). Both approaches are considered in the context of Friederici's (1995) three stage description of the ERP correlates of language processing. The basic findings provide evidence in favor of the three stage model and motivate an alternative account of Case ambiguity resolution.

1. CASE AMBIGUITY RESOLUTION

It has been noted that, on a variety of behavioral measures, subjects show differing responses to unexpected resolution of Case ambiguity dependent upon the source of the disambiguating information. One source is research on processing of German sentences containing Case ambiguous initial NPs (see also Sekerina (in press) for Russian). In the following examples the initial NP is ambiguous between Nominative and Accusative Case. There are two ways such an ambiguity can be resolved: via contrast with a morphologically Case marked second NP as illustrated in A or via number agreement or disagreement between NP1 and the verb, as illustrated in C. Example B below represents the unmarked condition in which the initial NP is the nominative argument of the sentence. All three sentences are unmarked and well formed in German. Examples such as those in A will be referred to as the Case condition. Examples such as those in B will be referred to as the Control condition and examples such as those in C will be referred to as the Number condition.

1.1 Matrix Constructions

A. Welche Frau besuchte der Richter

Which woman [sng] (Amb) visited[sng] the judge[sng] (Nom)

E. Witruk, A. D. Friederici, & T. Lachmann (Eds.), Basic Functions of Language, Reading, and Reading Disability, 41—60.

B. Welche Frau besuchte den Richter

Which woman[sng] (Amb) visited[sng] the judge[sng] (Acc)

C. Welche Frau besuchten die Richter

Which woman[sng] (Amb) visit[pl] the judges[pl] (amb)

A series of self paced reading and reaction time experiments examining such constructions (Hopf, Bayer, Bader, & Meng, 1998; Meng & Bader, 1996; Meng, 1998; Schlesewsky, 1997) showed a very stable reanalysis effect indicated by prolonged reaction times in the number condition, but no reliable reanalysis effect was found for the Case condition.

The first result is consistent with the well established preference to interpret an initial NP as subject. If NP1 is taken to be nominative then it should agree with the verb. A longer reading time or reaction time associated with a verb that does not agree in number with a Case ambiguous initial NP is consistent with this strategy. The second result is surprising. If NP1 is taken to be nominative, the occurrence of overt nominative marking on the second NP should cause some processing difficulty. This apparent lack of reaction to unexpected Case information has given rise to a rich discussion on the general nature of reanalysis and ambiguity resolution. Either the second Nominative is not noticed or discarded during language processing, or the reanalysis is so easy that it imposes no measurable cost. Both approaches have been proposed and both make differing predictions regarding the resolution of similar Case ambiguities in other constructions.

Expectation based or data based processing as proposed in Schlesewsky (1997) and Schlesewsky, Fanselow, Saddy, and beim Graben (1998) takes a cue validity approach to explaining the basic reaction time results. The strong reanalysis effect associated with the Number condition is accounted for as follows. The initial NP is strategically assumed to be nominative. The first available information that could bear on this decision is number agreement on the verb. If the verb does not agree in number with the initial NP, then the sentence is ungrammatical at this point and must be reanalyzed. The lack of an effect in the Case condition is explained by the late occurrence of the cue. The initial NP is strategically assumed to be nominative. In the Case condition the verb does have the same number marking as the initial NP thereby providing indirect support for its nominative status. The occurrence of a second nominatively Case marked NP leads to indeterminacy. The fact that the verb agrees in number with the initial NP leads the parser to discount the overt Case marking on the second NP. Two observations favor this approach: (1) The marking of number agreement in German is not ambiguous. The fact that the Case system in German contains systematic ambiguities[1] means that Case information is a weaker information source than number information. Thus the parser may be expected to value number information over Case information for ambiguity resolution. (2) Other studies (Meng & Bader, 1996) have shown that subjects are more sensitive to number marking than to Case marking in grammaticality judgements. Taken together these observations support the suggestion that Case is somehow a weaker information type than number in the constructions examined.

Alternatively, an information based or diagnosis and repair account (Fodor & Inoue, 1994, 1999a, 1999b) offers a modular approach. Number agreement and Case are two distinct information systems employed in language processing. Given the assumption of modularity, it should be more difficult to recognize and resolve parsing conflicts that cross modules than it is to recognize and resolve parsing conflicts that arise within only one module. Fodor & Inoue's account of the Number condition argues that the number agreement information carried by the verb provides a costly diagnosis of the Case strategically assigned to the initial NP. Furthermore, the number information provides no direct information regarding repair. The strategic assumption is that the initial NP is the subject of the upcoming predicate. The fact that the verb does not agree with the initial NP provides the information that the initial NP is not the subject of predication but it does provide or point to an alternative. The relative cost of using number information to resolve a Case ambiguity is reflected in the reaction time. The Case condition contrasts with the Number condition in both diagnosis and repair. The overt Nominative Case marking on the second NP bears directly on the Case of the first NP hence the diagnosis takes place within the same information system. Furthermore, the overtly Nominative second NP provides the repair. It is the new subject of predication. The lack of a reaction time effect associated with the Case condition reflects the comparative ease of the ambiguity resolution. We show below that evoked response potential recordings provide additional evidence relevant to the debate.

1.2 Interpreting Evoked Cortical Potentials

Recording the continuous voltage time series generated by the brain in response to varying but highly constrained stimuli now provides an important source of information about the time course of language processing and its functional fractionation. Friederici (1995, 1999) proposes a three-phase model for interpreting the behavioral markers associated with sentence processing. The model is based upon the systematic observations found in the voltage averaged responses in a wide range of ERP investigations as well as fMRI and MEG studies and provides an articulated guide to interpreting brain based responses in sentence processing. In Friederici's model, brain behavior associated with sentence processing detected in early time periods (120-200 ms) corresponds to a first pass parse. Brain behavior detected during the period ranging between 300 and 500 ms corresponds to semantic and thematic integration and diagnosis, while brain behavior detected in the later time periods, 500 to 900 ms, reflects structural repair or attempted repair processes. This model describes three fundamental steps necessary to sentence processing and connects them to particular time windows and voltage polarities. We interpret the model as providing a working guide to when to expect contrastive effects in the evoked time series. The results of the study described here provide new support for this model.

The recorded continuous EEG is a multivariate time series that is stored as a matrix containing the voltage time series associated with each of the recording electrodes arrayed across the scalp plus a channel containing trigger codes which mark the stimuli events in time. After filtering and artefact rejection the continuous EEG is split into epochs according to the trigger codes. Each epoch is a short time series consisting of the pre and post stimulus interval recorded to a single trial. These epochs are assembled into ensembles according to the contrasting experimental conditions. These procedures are common to the two analytic approaches employed here. The treatment of the data ensembles under the voltage averaging approach, which yields the standard ERP component analyses, and the CSC approach diverge significantly from this point on.

1.3 Voltage Averaged Markers (ERPs)

The voltage averaging approach characterizes the collected time series data in quantitative terms. What is the polarity of the voltages with respect to a reference electrode? How big is the amplitude of these deflections? When do these deflections take place? What is their topographic distribution? Four main markers of language processing have been identified in the literature; the ELAN, LAN, N400 and P600. They are identified by a nomenclature which refers to their polarity, post stimulus latency and topographic distribution. The early left anterior negativity or ELAN occurs between 120 and 220 ms with either a left or a bilateral anterior distribution. It is associated with strong phrase structure violations (Friederici, Pfeifer, & Hahne, 1993; Hahne, 1998; Neville, Nicol, Barss, Forster, & Garrett, 1991). The left anterior negativity or LAN has similar topography and polarity to the ELAN but occurs with a latency typically between 300 and 500 ms. The LAN is found in response to agreement violations (Coulson, King, & Kutas, 1998; Gunter, Stowe, & Mulder, 1997; Kutas & Hillyard, 1983; Osterhout & Mobley, 1995) and has been noted for Case violations on pronouns in English (Coulson et al., 1998). The N400 is a negativity with a latency peaking typically around 400 ms and having a centro-parietal bilateral distribution often with a slight right hemisphere focus. The N400 reflects the cost of semantic or thematic integration (Frisch, 2000, Kutas & Hillyard 1980a, b, 1983). The P600 or syntactic positive shift is a positivity occurring between 600 and 900 ms with a centro-parietal distribution and is associated with syntactic reanalysis (see Friederici, 1999; Friederici, Hahne, & Mecklinger, 1996; Hagoort, Brown, & Groothusen, 1993; Hahne & Friederici, 1999; Osterhout, 1997; Osterhout, McLaughlin, & Bersick, 1997)

The voltage averaging analysis is based on a number of assumptions. The central assumption underlying the averaging is that what is recorded is the evoked signal embedded in noise. Each ERP epoch is assumed to be a realization of a stochastic process which contains an invariant evoked signal. The evoked signal is assumed to be uncorrelated with the surrounding EEG activity. It is further assumed that there is no evoked signal in the pre-stimulus interval. Each recorded epoch is assumed to be a stationary and ergodic process. These assumptions are necessary in order to motivate the baseline correction calculation and subsequent signal averaging at the core of the traditional analysis. Baseline correction exploits the assumption that the pre-stimulus interval is uncorrelated with the evoked signal. The pre-stimulus interval therefore is representative of only the EEG noise in which the evoked signal is embedded. The time averages of the pre-stimulus intervals are subtracted from their corresponding epochs. What remains is presumed to be the signal evoked in response to the experimental stimuli. The evoked signal itself is very weak compared to the background EEG. In order to further improve the signal to noise ratio many trials per condition and per subject and many subjects per experiment are averaged together (typically 30 trials per condition and 16-20 subjects per experiment in sentence processing paradigms). The resulting averaged voltage time series are plotted and compared statistically to reveal systematic contrastive behavior generated in response to the experimental conditions. There are two central weaknesses associated with this approach. The first is that the basic assumptions outlined above are known to be false[2]. The second is that the averaging after baseline correction is affected by trial to trial variability in amplitude and onset latency. The consequence of this is that the traditional analysis necessarily underestimates contrastive behavior in the recorded signal (see beim Graben 2000 for a critical discussion of ERP analytic techniques). As a consequence of the inherent analytic weakness the standard ERP analyses provide a conservative but reliable picture of when contrastive cortical behavior might be found. Thus the standard voltage averaged analyses provides the basic framework from which other analytic approaches can be interpreted and judged.

2. CYLINDER ENTROPIES AND CONTRASTIVE SIGNAL COHERENCE (CSC)

We know that the brain behaves as a complex integrated system. Despite this, most of our techniques for analyzing the behavior we can measure in the cortex either assume the opposite or are insensitive to the complexity of the system. Previous attempts to apply the techniques of non-linear system analysis to electroence phalographic (or Magnetoencephalographic) recordings have shared one central flaw with the conventional subtractive techniques, that is the assumption of stationarity of the system or ergodicity in the data stream. beim Graben, Liebscher and Saddy (2000) develop a technique which does not have this shortcoming. This approach which identifies changes in signal coherence in response to experimental stimuli, rests upon the calculation of Cylinder Entropies (beim Graben, 2000; beim Graben, Saddy, Schlesewsky, & Kurths, 2000). This non-linear technique provides a measure of the change in information entropy associated with the signals generated by the processing system over time. More precisely, the Cylinder Entropies provide a measure of changes in phase or state space volume. Episodes of Contrastive Signal Coherence (CSC) as identified by the calculation of Running Cylinder Entropies reveal temporal and topographic coherency analogues of the ERP components in the signal as well as revealing contrastive signal behavior that cannot be identified with ERP components. In addition the technique provides a significant signal to noise improvement. Thus the computation of CSC can enhance the ERP based view of cortical behavior.

The idea of applying the techniques of non-linear system analysis to brain recordings is not new (see Albano et al., 1986; Babloyantz, Salazar, & Nicolis, 1985; Basar, Flohr, Haken, & Mandell, 1983; Bullmore et al., 1994; Freeman, 1990; Gallez & Babloyantz, 1991; Layne, Mayer-Kress, & Holzfuss, 1986; Lutzenberger, Elbert, Birbaumer, Ray, & Schupp, 1992; Pritchard & Duke, 1992). Most approaches have used the estimation of correlation dimension as a method for determining the change in computational complexity of a given brain process. This and related approaches have proved to have limited applications because the calculation of correlation dimensions requires the measurement of a stationary system (see Molnár, Skinner, Csépe, Winkler, & Karmos, 1995 for another approach

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