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A predictive coding framework for rapid neural dynamics during sentence-level language comprehension

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ABSTRACT

There is a growing literature investigating the relationship between oscillatory neural dynamics measured using electroencephalography (EEG) and/or magnetoencephalography (MEG), and sentence-level language comprehension. Recent proposals have suggested a strong link between predictive coding accounts of the hierarchical flow of information in the brain, and oscillatory neural dynamics in the beta and gamma frequency ranges. We propose that findings relating beta and gamma oscillations to sentence-level language comprehension might be unified under such a predictive coding account. Our suggestion is that oscillatory activity in the beta frequency range may reflect both the active maintenance of the current network configuration responsible for representing the sentence-level meaning under construction, and the top-down propagation of predictions to hierarchically lower processing levels based on that representation. In addition, we suggest that oscillatory activity in the low and middle gamma range reflect the matching of top-down predictions with bottom-up linguistic input, while evoked high gamma might reflect the propagation of bottom-up prediction errors to higher levels of the processing hierarchy. We also discuss some of the implications of this predictive coding framework, and we outline ideas for how these might be tested experimentally.

1. Introduction

Reading, or listening to someone speaking, are the simple kinds of tasks that most people engage in every day of their lives without much difficulty. Yet if one considers that the average reader can easily manage between 250 and 300 words per minute (e.g., Rayner, Pollatsek, Ashby, & Clifton, 2012), it becomes clear that the processing carried out by the language comprehension system must be extremely fast and dynamic.

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One possible explanation for this speed (to be sure, one among many) is that the system may make predictions about upcoming linguistic input. From such a perspective it is surprising that models of language comprehension based on the passive building up of semantic and syntactic structures (from the lexical building blocks activated upon perception of linguistic input) dominated the psycholinguistics literature for so long (e.g., Forster, 1981; Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Zwitserlood, 1989). Arguments that prediction was not likely to be involved in language comprehension were generally made based on the observation that at any point while reading or listening there are a large number of possible continuations. Processing costs involved in making incorrect predictions, along with the presumed low percentage of benefits accrued (predictions would not often be correct) made predictive processing accounts unappealing (see van Petten & Luka, 2012 for discussion).

On the other hand, a large number of studies began to show that the processing of a word in a sentence can be facilitated by the constraining sentence context (sometimes even before the word can be uniquely identified; e.g., Altmann & Kamide, 1999, 2007; Balota, Pollatsek, & Rayner, 1985; van den Brink, Brown, & Hagoort, 2001; Ehrlich & Rayner, 1981; Federmeier & Kutas, 1999; Kamide, 2008; Kamide, Altmann, & Haywood, 2003; Kamide, Scheepers, & Altmann, 2003; Knoeferle, Crocker, Scheepers, & Pickering, 2005; MacDonald, Pearlmutter, & Seidenberg, 1994; McRae, Hare, Elman, & Ferretti, 2005; van Petten, Coulson, Rubin, Plante, & Parks, 1999; Schwanenflugel & Lacount, 1988; Sussman & Sedivy, 2003). The idea that predictive processing could, at least in some circumstances, be beneficial for language comprehension has slowly grown in popularity. By now the notion that (at least some of the time) prediction plays an important role in rapid, dynamic, real-time language comprehension is a widely accepted view (Pickering & Garrod, 2007).

However, within this emerging view there are many outstanding questions. For instance, what are the details about exactly when prediction plays a role (is the system always making predictions or only under certain circumstances when this may be a useful strategy?). How do predictions interact with real-time comprehension? What kinds of information might lead to (strong) predictions? And, crucially, how does the brain implement predictive processing? While we briefly discuss each of these questions we acknowledge that it is not possible to do justice to them all in a single review. The main focus of this review is to outline some ways in which we think that the study of electrophysiology, and in particular oscillatory neural dynamics measured using electroencephalography (EEG) and magnetoencephalography (MEG) can contribute to our understanding of predictive processing during language comprehension beyond the level of individual words.

1.1. *Event-related potential (ERP) studies and prediction during sentence comprehension*

In the last ten to fifteen years a number of ERP studies have investigated the potential role of prediction during sentence-level language comprehension (see e.g., van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; DeLong, Urbach, & Kutas, 2005; Otten, Nieuwland, & Van Berkum, 2007; Szewczyk & Schriefers, 2013; Wicha, Moreno, & Kutas, 2004). The common ingredient used in all these studies to investigate predictive processing was agreement relations between a particular noun and some element preceding the noun. If the constraining sentence context allows readers/listeners to make predictions about the following noun, then lexical information associated with that noun should be available to the comprehension system before the noun is presented and should have an influence on the processing of agreement relations between the noun and the element preceding it.

An effect of prediction on ERP responses has been shown in the context of both gender-marked determiners (Wicha et al., 2004), and adjectives (van Berkum et al., 2005; Otten et al., 2007) preceding some highly expected noun in strongly constraining sentence contexts. These congruity (congruous or incongruous gender agreement) effects prior to the presentation of the word eliciting them are not the result of simple word-priming (Otten et al., 2007) and can occur more than a single word in advance of the target noun (van Berkum et al., 2005). Along similar lines, the effects of prediction on ERP responses have been shown to be graded in nature (DeLong et al., 2005), dependent on the target noun's cloze probability (a normative measure that in most circumstances can be taken as a proxy for how predicted a particular word is in a given sentence context; cf., Kutas & Federmeier, 2011). In addition to grammatical (van Berkum et al., 2005; Otten et al., 2007; Wicha et al., 2004) and phonological (DeLong et al., 2005) information, it has recently been shown that semantic information (in this case the semantic class of animacy) about an upcoming noun may also be predicted, and has an effect on ERP responses before the target noun (Szewczyk & Schriefers, 2013).

Taken together these studies make a strong case for (graded) predictions during sentence-level language comprehension, and not simply predictions about particular words but also about (at least some) semantic categories of words. They also show that electrophysiological brain responses (in this case ERPs) are sensitive to (at least some of) the processing consequences of these predictions.

In addition to syntactic features associated with specific lexical items (e.g., gender or number marking), other non-local syntactic dependencies may also lead to predictive processing, and the prediction of particular syntactic structures. For example, one prominent account of the P600 ERP component is as a reflection of processes of reanalysis and repair (e.g., Friederici, 2002; Friederici & Mecklinger, 1996). A P600 effect has been reported in the case of syntactic garden path sentences (e.g., Osterhout, Holcomb, & Swinney, 1994), for syntactic ambiguity resolution with object-compared to subject-relative clauses (Mecklinger, Schriefers, Steinhauer, & Friederici, 1995), and for syntactic violations (Hagoort, Brown, & Groothusen, 1993). All these cases have in common that they involve a preferred syntactic structure that is constructed and needs to be revised or repaired at a point where the input indicates that it is not correct (Friederici & Mecklinger, 1996). Although they have not traditionally be interpreted in this way, it is possible to argue that all these cases involve a prediction (by the language comprehension system) that a particular syntactic construction will