Neuropsychologia 102 (2017) 70–81

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Internal mechanisms underlying anticipatory language processing: Evidence from event-related-potentials and neural oscillations

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ARTICLE INFO

Keywords:
Predictive processing
Anticipatory language processing
Brain oscillations
Top-down modulation

ABSTRACT

Although numerous studies have demonstrated that the language processing system can predict upcoming content during comprehension, there is still no clear picture of the anticipatory stage of predictive processing. This electroencephalograph study examined the cognitive and neural oscillatory mechanisms underlying anticipatory processing during language comprehension, and the consequences of this prediction for bottom-up processing of predicted/unpredicted content. Participants read Mandarin Chinese sentences that were either strongly or weakly constraining and that contained critical nouns that were congruent or incongruent with the sentence contexts. We examined the effects of semantic predictability on anticipatory processing prior to the onset of the critical nouns and on integration of the critical nouns. The results revealed that, at the integration stage, the strong-constraint condition (compared to the weak-constraint condition) elicited a reduced N400 and reduced theta activity (4–7 Hz) for the congruent nouns, but induced beta (13–18 Hz) and theta (4–7 Hz) power decreases for the incongruent nouns, indicating benefits of confirmed predictions and potential costs of disconfirmed predictions. More importantly, at the anticipatory stage, the strongly constraining context elicited an enhanced sustained anterior negativity and beta power decrease (19–25 Hz), which indicates that strong prediction places a higher processing load on the anticipatory stage of processing. The differences (in the ease of processing and the underlying neural oscillatory activities) between anticipatory and integration stages of lexical processing were discussed with regard to predictive processing models.

1. Introduction

When interacting with the environment, we use available information continuously to predict upcoming events and reduce uncertainty. Predictive processing is essential for successful everyday interaction. Recently, the role of prediction in visual or auditory sensory processing has received lots of attention, and some models have been put forward to account for the cognitive and neural mechanisms of predictive processing (e.g., Bever and Poeppel, 2010; Knill and Pouget, 2004; Friston, 2005). Prediction also plays a very important role in language comprehension. Numerous studies have demonstrated that readers or listeners can form semantic predictions about which content word or concept is going to appear next (Van Berkum et al., 2005; DeLong et al., 2005), and this kind of semantic prediction can facilitate language comprehension. However, existing studies on predictive language processing mainly focus on processing of predictable words themselves, rather than on the anticipatory processes that should precede prediction (e.g., Laszlo and Federmeier, 2009; Thornhill and Van Petten, 2012). There is still no clear picture of what happens before the predicted/unpredicted words appear in the incoming language input. The present study, focused on the mechanisms underlying the anticipatory stage of semantic prediction during language comprehension.

In the field of psycholinguistics, the effect of prediction on language comprehension has been studied extensively in both reading and speech comprehension. ERP (event-related brain potential) studies have demonstrated that predictability of critical words in sentence or discourse contexts modulate the amplitude of the N400, such that a reduced N400 is found to words that are highly predictable relative to words that are not (Besson et al., 1992; Boudewyn et al., 2015; Diaz and Swaab, 2007; Federmeier, 2007; Laszlo and Federmeier, 2009; Thornhill and Van Petten, 2012; Szewczyk and Schriefers, 2013). The classical N400 effect has a centro-parietal distribution and reaches its maximum amplitude

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http://dx.doi.org/10.1016/j.neuropsychologia.2017.05.017
Received 13 October 2016; Received in revised form 10 May 2017; Accepted 14 May 2017
Available online 15 May 2017
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around 400 ms after the onset of the stimulus. It is sensitive to semantic aspects of the linguistic input and is modulated as a function of the ease of semantic processing, with an increase in amplitude indicating more difficult processing (Hagoort and Brown, 2000; Kutas and Van Petten, 1994). The sustained anterior negativity (SAN), has also been found to increase in amplitude during difficult language processing (Nieuwland and Van Berkum, 2006; Van Berkum et al., 1999a, 2003). Therefore, the reduced N400 observed in the above studies reflects the benefits of confirmed prediction.

Another line of ERP studies observed prediction effect at the location of words preceding a predictable noun, such as pronominal adjectives or determiners that indicate the gender or phonological properties of this noun. For example, DeLong and colleagues observed a reduced N400 on a determiner ("a" or "an") that was consistent with the following predictable noun as compared to an inconsistent determiner (e.g. when "kite" was predicted as in "The day was breezy so the boy went outside to fly …", "a" versus "an") (DeLong et al., 2005). This kind of prediction effect observed at adjectives or determiners that precede the predictable noun has been replicated in quite a few studies, with some showing reduced N400 (Szewczyk and Schriefers, 2013; Wicha et al., 2003) or right-frontal N400-like negativity (Otten et al., 2007) and others showing reduced widely-distributed positivity on the consistent adjectives/determiners (late positivity in Wicha et al. (2004); positivity starting relatively in Van Berkum et al. (2005)). The reduced negativity or positivity reflects the facilitating effect of prediction on language comprehension. Overall, the existing results indicate that, during reading or speech comprehension, the language processing system can form semantic predictions about upcoming words in the context, which can facilitate the processing of the predicted bottom-up signal.

Several models or hypothesis have been put forward to account for predictive processing. Recently, the idea of analysis by synthesis (A × S) and the Bayesian approach have gained increasing attention in the literature on cognition and perception, including the domains of visual perception and language processing. The A × S model proposes that the language processing system actively generates hypothesized candidate representations on the basis of given information (synthesis). These internally generated hypotheses are matched against the incoming bottom-up language signals (analysis). A distinct feature of A × S model is that it emphasizes an internal predictive step in language comprehension (the synthesis stage) (Halle and Stevens, 1959; Stevens and Halle, 1967; Townsend and Bever, 2001; Bever and Poeppel, 2010; Poeppel and Monahan, 2011). The idea of A × S aligns well with the Bayesian approach, which assumes that our brains combine prior knowledge and contextual information to calculate the posterior likelihood of the presence of an object (or a word) being presented in the forthcoming input (Knill and Pouget, 2004; Friston, 2005). Therefore, both the A × S model and the Bayesian approach view prediction as a consequence of an internal generative process by which the human brain draws upon given information to construct hypothesized candidate representations of the forthcoming information.

According to the assumptions of A × S model and Bayesian approach, there are in fact two stages of predictive processing. That is, the human brain, on the one hand, uses available information to calculate hypothesized candidate representations of forthcoming content (anticipatory stage), and on the other hand, constantly tests and updates these internal representations by integrating new bottom-up inputs with the top-down predictions (integration stage) (e.g., Halle and Stevens, 1959; Stevens and Halle, 1967; Poeppel and Monahan, 2011; Knill and Pouget, 2004; Friston, 2005). In the field of psycholinguistics, although the existing studies consistently have demonstrated the facilitating effect of prediction on language comprehension, they have mainly focus on the integration stage of prediction (Besson et al., 1992; Diaz and Swaab, 2007; Federmeier, 2007; Laszlo and Federmeier, 2009; Thornhill and Van Petten, 2012; Szewczyk and Schriefers, 2013). There is still no clear picture of what happens at the anticipatory stage of predictive processing (namely, before the predicted/unpredicted information appears in the bottom-up signal). First, we do not know how the ease of the anticipatory stage of processing changes as a function of semantic predictability. Will the anticipatory and integration stages of language processing be influenced by semantic predictability in the same way? One possibility is that, in a strongly constraining context (relative to a weakly constraining context), the human brain has more supporting information to calculate the hypothesized candidate representations of the forthcoming signal, and consequently, this calculating process might be conducted more easily. This would predict that the anticipatory stage of processing, like the confirmed predictions at the integration stage, is facilitated by strong predictions. Another possibility is that, calculating or maintaining the hypothesized candidate representations at the anticipatory stage might consume more working memory resources, which would predict that strong predictions, place a higher processing load on anticipatory processing. Thus, the effect of predictability on the anticipatory stage of processing still needs to be explored.

Second, the existing studies on predictive language processing mainly focused on the ERP responses of prediction, and less is known about the neural oscillatory activities associated with semantic prediction. Unlike ERPs that reflect only neural activity that is phase-locked to the stimulus, the oscillatory brain activities reflect both the phase-locked and non-phased-locked activity. Moreover, the synchronization/desynchronization patterns of neural oscillations have been shown to reflect specific aspects of cognitive operations. For example, decreased synchronization in the theta band (4–7 Hz) has been considered to be associated with facilitated lexical-semantic processing (Bastiaansen et al., 2005; Davidson and Indefrey, 2007). Beta oscillations have further been found to play an important role in top-down control processes (Arnal and Giraud, 2012; Fujioka et al., 2012; de Lange et al., 2013; Arnal et al., 2014; Friston et al., 2015), with an increase in beta activity signaling that the processing system is actively maintaining the current cognitive set and a decrease in beta activity signaling that the current mode of processing is expected to change (Engel and Fries, 2010; for review see Lewis et al. (2015, 2016)). However, it is still not completely clear which frequency-band of (and which specific pattern of) neural oscillatory modulations are associated with the anticipatory stage of predictive language processing. Answering this question can help us gain a deeper understanding of the cognitive nature of anticipatory language processing.

With respect to the integration stage of predictive language processing, there is a lot of evidence supporting the facilitating effect of predictability on the processing of bottom-up signals. In fact, during reading or speech comprehension, the human brain tests and updates its top-down hypothesized representations by processing not only the confirmed predictions but also prediction errors. However, it is currently less clear whether there are potential processing costs for disconfirmed predictions during the integration stage. That is, will disconfirmed predictions be more difficult to deal with in the highly constraining than in the weakly constraining contexts? Although there is consistent evidence for the benefits of confirmed predictions, fewer studies have reported the costs of disconfirmed predictions. For example, Federmeier and colleagues observed enhanced late positivity for unexpected endings in strongly constraining sentences, indicating cognitive costs for integrating disconfirmed predictions (Federmeier et al., 2007). A recent study also found that an enhanced frontal post-N400 positivity (PNP) was evoked by unpredicted items (compared to prediction items) during reading comprehension, suggesting the costs of revising discourse representations following an incorrect lexical prediction (Brothers et al., 2015).

The present EEG (electroencephalograph) study was conducted to further examine the effect of prediction processing on language comprehension. The most important aim of this study was to examine whether semantic predictability indeed affects anticipatory language processes, and if so to examine the neural oscillatory activity that is

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