Frontiers in ERP-Based Research on Predictive Sentence Processing

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Abstract

This paper reviews the major achievements and important breakthroughs in international journal publications that have employed event-related potential (ERP) technology to investigate predictive sentence processing in the human brain. Beginning with the research logic underlying psycholinguistic studies of sentence prediction, it respectively examines research milestones that have illuminated the two primary operations of predictive sentence processing—lexical form prediction and semantic prediction—through the two ERP effects of N400 and frontal positivity, and subsequently summarizes and outlines a theoretical model of predictive sentence processing. Finally, this paper identifies the limitations of existing research and potential future directions for this topic.

Full Text

Preamble

Frontiers in ERP-based Research on Predictive Sentence Processing

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Abstract: This paper reviews the primary findings and breakthroughs in the study of predictive sentence processing using event-related potentials (ERPs). Our review begins by introducing the rationale underlying sentence prediction research in psycholinguistics. We then survey the milestones that have revealed the associations between two major predictive processes and their ERP correlates: the N400 and frontal positivity effects. A model of predictive sentence processing is synthesized based on previous studies. Finally, we discuss the limitations of existing research and propose possible directions for future investigation.

Key words: sentence comprehension; prediction; N400; frontal positivity; event-related potential (ERP)

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1. Introduction

During language transmission, the constituent words of a sentence follow a specific linear order as they enter the cognitive system. However, the sentence comprehension system does not appear to passively process incoming words. Instead, it can dynamically engage in top-down processing of upcoming sentence continuations by integrating contextual information. For example, given the English context "The child was born with a rare ···," either "disease" or "gift" would make the sentence coherent, yet "disease" seems to better match certain expectations (Federmeier et al. 2007). What specific linguistic-cognitive operations this "expectation" in sentence comprehension entails has long puzzled psycholinguists. In recent years, by employing event-related potential (ERP) technology with its exceptionally high temporal resolution and ingenious experimental designs, researchers have not only confirmed that the sentence comprehension system can efficiently utilize contextual cues to make specific "predictions" about upcoming words (Federmeier 2007; DeLong et al. 2011; Van Petten & Luka 2012), but have also discovered that such "predictions" generate expectations for specific continuations that subsequently influence the online processing of actual input words that either match or violate these predictions. This type of processing is termed predictive sentence processing (Kaan, 2014). This paper focuses on reviewing how existing ERP studies have addressed two fundamental questions: "Does prediction exist in sentence comprehension?" and "What are the cognitive implications of predictive sentence processing?" We then summarize the theoretical models of predictive sentence processing and outline future research directions.

2. Background on ERP-based Sentence Processing Research

Over the past three decades, ERP technology has made it possible to monitor online sentence comprehension as a high-level human cognitive activity. Among the numerous ERP components associated with language processing, the most robust are undoubtedly the N400 and P600. The N400 is a negative-going wave typically observed in a time window centered around 400ms post-stimulus onset (spanning approximately 200ms), widely considered to reflect semantic processing (Kutas & Federmeier 2011; Kutas & Hillyard 1980, 1984). When an input word creates syntactic infelicity, a positive-going slow potential emerges around 600ms post-stimulus, known as the P600, which has been shown to relate to syntactic processing difficulty (Gouvea et al. 2010; Hagoort et al. 1993; Kaan et al. 2000; Osterhout & Holcomb 1992). Additionally, under reading conditions, both N400 and P600 typically exhibit a central-parietal scalp distribution.

Based on these two neurophysiological indices, mainstream sentence processing theories represented by Friederici (2002) and Hagoort & Van Berkum (2007) have generally adopted a "semantic-syntactic" dichotomy framework (Van Petten & Luka, 2012). This perspective holds that sentence processing essentially involves integrating the semantic (conceptual) and syntactic (structural) dimensions of constituent words into the evolving context. Specifically, to comprehend a sentence, the parser decodes the semantic and syntactic information of an incoming continuation and integrates it with the accumulating context. According to the distinct temporal characteristics of N400 and P600, such theories further propose that semantic processing temporally precedes syntactic processing, and that these are independent cognitive mechanisms that operate sequentially (Frisch et al. 2004).

However, the sentence comprehension system appears to do more than simply "integrate" the semantic and syntactic features of continuations into dynamically growing contextual information—it can actually predict a specific candidate word based on context. Testing for the existence of sentence prediction requires two types of evidence: first, facilitation effects when predictions are successful, and second, additional cognitive costs when predictions fail (DeLong et al. 2011; Van Petten & Luka 2012). As the association between sentence processing and ERPs became established, ERP technology was rapidly adopted to explore sentence prediction. Leveraging ERPs' exceptional temporal resolution and sensitivity to cognitive processing, researchers overcame the limitations of traditional behavioral methods, successively discovering electrophysiological evidence supporting predictive sentence processing under both successful and unsuccessful prediction scenarios, thereby prompting revisions to sentence comprehension theories. Below, we introduce the ERP effects corresponding to successful and unsuccessful predictions and analyze the cognitive implications of predictive sentence processing.

3. Successful Sentence Prediction and the N400

Numerous studies comparing ERP responses to high- versus low-predictability sentence continuations have found that the amplitude of the N400 elicited by a continuation word negatively correlates with its predictability (Kutas & Hillyard 1984; Federmeier et al. 2007; Thornhill & Van Petten 2012; DeLong et al. 2014; Ito et al. 2016). That is, higher predictability leads to smaller N400 amplitudes. Since more pronounced N400 effects typically correspond to greater semantic processing difficulty, this negative correlation suggests that predictive sentence processing facilitates semantic processing.

Further evidence indicates that this correlation between N400 and predictability arises from predicting specific candidate words. On one hand, researchers have examined semantic processing of continuations with varying predictability under different levels of contextual constraint (Kutas & Hillyard 1984; Federmeier et al. 2007; Thornhill & Van Petten 2012). Contextual constraint is a psycholinguistic metric that measures how many continuation words can felicitously complete a given sentence frame—the stronger the constraint, the fewer acceptable candidate continuations exist. For example, when reading "Mary went to her room to look at her ···," most people would complete it with "clothes" (Federmeier et al. 2007), though some might respond with "gift," "sister," "toy," or other varied continuations, indicating weak contextual constraint. ERP data reveal that regardless of contextual constraint strength, low-predictability continuations elicit larger N400s than high-predictability sentence completions, with no significant difference in N400 amplitude for low-predictability continuations across high- and low-constraint contexts. These results suggest that the brain does not pre-activate all semantically related representations but can make precise, specific predictions about the most likely upcoming word based on context (Federmeier et al. 2007; Thornhill & Van Petten 2012).

On the other hand, if the sentence comprehension system can predict a specific candidate word, activation of that word' s semantic concept must influence processing of the actual continuation. Based on this hypothesis, researchers designed the semantic relatedness anomaly paradigm. Initially, theories such as "automatic semantic activation" (Kutas & Van Petten 1988; Brown & Hagoort 1993) proposed that all contextually related semantics become automatically activated during sentence comprehension, thereby affecting continuation processing. In other words, contextually "activated" semantics should influence processing of different anomalous words equally, without differential processing difficulty. However, later research found that in specific contexts, even when several types of anomalous words are all unrelated to the context, the brain processes those more closely related in meaning to the expected candidate word more easily, with semantically related anomalous words eliciting significantly smaller N400s than unrelated ones (Federmeier & Kutas 1999; Ito et al. 2016).

In summary, the negative correlation between N400 and continuation predictability results from predicting specific words, and this cognitive process activates conceptual representations of predicted words, thereby facilitating semantic processing of both successfully predicted input words and semantically related anomalous words. Thus, in predictive sentence processing, the N400 reflects predictive activation of conceptual semantics.

4. Unsuccessful Prediction and Frontal Positivity

While revealing the association between successful prediction and the N400, research has also found that when the actual input continuation mismatches the high-predictability candidate but still yields a coherent sentence, such stimuli typically elicit a positive-going ERP effect with a latency of approximately 400-600ms that can persist until 900-1200ms, distributed over anterior scalp electrodes (Coulson & Van Petten 2007; DeLong et al. 2011, 2012, 2014; Federmeier et al. 2007; Ito et al. 2016; Rommers & Federmeier 2018; Kutas 1993; Thornhill & Van Petten 2012; Wicha et al. 2004; Van Berkum et al. 2005), showing some left-hemisphere lateralization (DeLong et al. 2011; DeLong & Kutas 2016; Rommers & Federmeier 2018). Since late positive waves in ERPs often reflect additional cognitive costs, this anterior positivity was initially thought to result from expectation revision triggered by prediction failure (Kutas 1993). Subsequently, Federmeier et al. (2007) explicitly reported a positive slow potential beginning at 500ms latency following unsuccessful predictions, naming it frontal positivity. Because this frontal positivity is typically observed in a time window approximately 100ms after the N400 peak, it is also termed "Post-N400 Positivity" (PNP; Van Petten & Luka 2012: 183).

Existing research has revealed the association between frontal positivity elicited by prediction failure and lexical form prediction from two perspectives. First, the frontal positivity evoked by unexpected input words appears unaffected by contextual semantics (Federmeier et al. 2007; Thornhill & Van Petten 2012). Thornhill & Van Petten (2012) compared brain responses to expected words, semantically related low-expectancy words, and semantically unrelated low-expectancy words under high- and low-contextual constraint conditions. For example, in the high-constraint sentence "He was afraid that doing drugs would damage his brain / mind / reputation," and the low-constraint sentence "Penelope started to assemble her new bicycle but was missing the wheels / tires / instructions,"where underlined words correspond to the three continuation types respectively. Results showed that although semantically related low-expectancy words elicited smaller N400 effects than unrelated ones, this semantic relatedness did not affect the amplitude of frontal positivity they evoked. Moreover, frontal positivity elicited by low-expectancy continuations was insensitive to contextual constraint strength.

Second, researchers have cleverly designed experimental materials that conflict with expected candidates'morphological requirements by exploiting rich morphosyntactic rules across languages (e.g., the English indefinite article a/an constraint on the initial phoneme of subsequent nouns), and have consistently found stable frontal positivity effects (DeLong et al. 2011; Van Berkum et al. 2005; Wicha et al. 2004). Thus, when the actual continuation' s morphology is inconsistent with expectations, the input word elicits frontal positivity, reflecting that the sentence comprehension system can conduct online verification of predicted words' lexical forms and morphological requirements, recruiting additional cognitive resources to revise previous predictions when they fail.

Furthermore, recent research has investigated prediction failure for high-expectancy candidates. For instance, Nessa & Asschera (2018) found that when high-expectancy candidates fail to materialize, frontal positivity reveals that the brain inhibits the expected candidate, thereby affecting integration of the actual, felicitous continuation. Ungrammatical expressions, however, do not elicit this candidate-inhibiting frontal positivity. Additionally, Rommers & Federmeier (2018) extended experimental materials from single sentences to multi-sentence passages, re-presenting previously predicted-but-not-presented candidates in subsequent text, and found that these reappearing expected candidates elicited enhanced N400s in specific contexts.

5. Mechanisms of Predictive Sentence Processing

The ERP studies reviewed above vividly demonstrate that sentence comprehension involves predicting specific upcoming continuations. The core of this predictive mechanism entails forecasting continuations along two dimensions: semantic-conceptual and lexical form. Specifically, the sentence comprehension system can generate a dedicated candidate word based on context. Both the semantic concept and lexical form carried by the predicted word are pre-activated and influence cognitive processing of the actual input word. Sentence comprehension benefits from successful predictions, manifested as reduced N400 amplitudes for high-predictability continuations, indicating lower conceptual processing difficulty for expected versus unexpected words. Unsuccessful predictions, conversely, trigger not only larger N400s but also significant frontal positivity, suggesting that the sentence comprehension system predicts the lexical form dimension of expected words. This likely involves the following operations: the system first verifies the actual input word' s form against the predicted word' s form, and when a mismatch occurs, additional cognitive costs are incurred to inhibit the pre-activated lexical form, thereby enabling processing of the unexpected input.

The temporal information revealed by ERP data also clearly shows that predictive sentence processing exhibits a characteristic pattern of stepwise initiation with partial overlap. Specifically, predictive semantic-conceptual processing of the input continuation occurs in a time window centered around 400ms post-stimulus (the N400 window). The impact of lexical form prediction begins approximately 400ms after continuation onset, peaking around 500-600ms. This time window falls precisely between semantic processing (N400) and syntactic processing (P600), suggesting that predictive lexical form processing unfolds after semantic processing begins but before syntax-related processing commences. The distinct scalp distributions of frontal positivity and N400 further indicate that predictive lexical form processing, while separable from conceptual-semantic processing, can operate in parallel.

ERP research on predictive sentence processing has substantially enriched sentence comprehension theory. First, predictive theory delineates two linguistic-cognitive computational mechanisms–semantic prediction and lexical form prediction—refining traditional "integration" operations and mapping them onto N400 and frontal positivity effects, thereby revealing the architecture of the language-cognitive system at a more microscopic scale. Second, the temporal dynamics uncovered by ERP technology suggest that predictive sentence processing operates not in the strictly sequential manner described by traditional theories (Friederici 2002; Friederici & Weissenborn 2007), but rather through a hybrid model combining stepwise and parallel processing, better characterizing the dynamic structure of sentence comprehension. Third, predictive sentence processing theory further elucidates how contextual information constrains sentence comprehension across both meaning and form dimensions. Specifically, context provides various cues for unfolding sentence comprehension and triggers predictions about specific continuations, with predicted content encompassing both lexical form information and complete semantic information to satisfy contextual constraints.

6. Limitations of Existing Research

Limitations of existing ERP research on predictive sentence processing manifest in four areas: linguistic interpretation, modality generalizability, conditions for eliciting prediction-related ERPs, and applied research. First, although ERP studies have successfully isolated electrophysiological effects related to semantic and lexical form prediction, revealing the cognitive nature of predictive processing, these discussions remain insufficient. The sentence structures examined have been relatively simple and do not fully match the rich variety found in real-life language use. Only a few studies have addressed this issue. For example, Freunberger & Roehm (2016) found that semantic concepts carried by adverbial modifiers also influence processing of actual continuations, with stronger ERP responses elicited by continuations in high-constraint contexts. This finding challenges the theoretical assumption that "N400 amplitude negatively correlates with continuation predictability" and raises questions about the cognitive mechanisms underlying actual language processing. Additionally, existing research has rarely addressed the linguistic details upon which predictive sentence processing relies. Predictive processing is sensitive to semantic and morphological information, and its electrophysiological responses differ markedly from those elicited by unexpected or novel non-linguistic physical stimuli, demonstrating language specificity. We therefore propose that context' s ability to predict semantic and lexical features of sentence continuations is determined by the syntax-semantics interface structure in specific contexts (Hackl, 2013). More specifically, accumulating contextual input provides the sentence comprehension system with information about likely argument structures, phrase structures, and other constructional requirements, as well as lexical-semantic demands that best match the meaning of the current construction (Goldberg 2003). A high-expectancy word in a given context best satisfies these requirements both formally and semantically, and thus becomes pre-activated. Further research must first establish that the syntax-semantics interface within constructions provides the linguistic impetus for predictive sentence processing, and then examine how constraints from constructions at different scales coordinate and interact to influence sentence prediction when combined into sentences.

Second, ERP research revealing predictive sentence processing mechanisms has almost exclusively used reading paradigms, raising questions about the generalizability of these findings (Van Petten & Luka 2012). While sentence comprehension in visual and auditory modalities is generally thought to rely on the same cognitive mechanisms (Kuperberg 2007), reading paradigms differ substantially from natural reading, often presenting stimuli at fixed rates and intervals word-by-word, meaning that ERP effects discovered in reading paradigms might result from task-specific artifacts. A handful of studies have reported predictive processing in auditory sentence comprehension (Boudewyn et al., 2015; Freunberger & Nieuwland, 2016; Drake & Corley, 2015). For instance, Boudewyn et al. (2015) found that auditory continuations with different expectancy levels elicited graded N400 responses, and that prediction failure elicited frontal positivity only in high-predictability contexts.

Third, the triggering conditions for ERP effects related to predictive sentence processing remain insufficiently investigated. Although recent proposals suggest that sentence comprehension fundamentally involves predictive activation of linguistic representations at multiple scales (Kuperberg & Jaeger 2016), predictive processing as a context-dependent cognitive activity necessarily requires certain conditions to be triggered. For example, Ito et al. (2016) found that stimulus onset asynchrony (SOA) duration affects prediction-related N400 manifestations. Their results showed that in predictive sentence contexts, when SOA was long (700 ms), continuations semantically or lexically related to expected words elicited weaker N400 responses than unrelated continuations, whereas with short SOA (500 ms), reduced N400 effects were found only for semantically related continuations. These findings suggest that predictive sentence processing patterns are influenced by how continuations are presented. Additionally, based on literature review, researchers have concluded that only low-predictability continuations that preserve sentence felicity can elicit frontal positivity (Thornhill & Van Petten 2012; DeLong et al. 2014; Rommers & Federmeier 2018), whereas continuations causing grammatical violations more likely trigger P600 effects (Van Petten & Luka 2012). This clearly contradicts researchers' claim that "lexical form prediction is an independent cognitive mechanism," because if predictive processing were a stable mechanism, frontal positivity should be observed whenever lexical form prediction fails. Moreover, because syntactically anomalous continuations typically elicit P600, few studies have simultaneously examined both P600 and frontal positivity, leaving the relationship between predictive lexical form processing and syntax-related processing unclear and providing insufficient support for cognitive interpretations of frontal positivity. Furthermore, existing research has focused exclusively on sentence-final words as critical items for observing predictive sentence processing ERPs, lacking comparisons across different sentence positions. Therefore, how to reliably elicit ERP effects related to predictive sentence processing has become a question that future research must address.

Finally, it is essential to characterize predictive sentence processing across populations differing in age, health status, and language background. For example, DeLong et al. (2011) pioneered comparisons of ERP responses to high- and low-predictability content words and preceding articles between fluent and nonfluent older adults. They found that, similar to young adults, older adults showed N400 sensitivity to predictability for content words, with fluent older adults exhibiting even larger and longer-latency frontal positivity than young adults. However, unlike young adults, older adults' ERPs were insensitive to articles morphologically inconsistent with high-expectancy content words. These results clearly indicate that older adults' sentence comprehension mechanisms retain conceptual and lexical form prediction functions, but these functions are limited to content words and require more cognitive resources to revise lexical form predictions when they fail. Chang et al. (2016) further found that ERP effects of predictive processing correlate with reading ability in aphasic populations, suggesting potential clinical applications for sentence prediction and its electrophysiological markers.

Although few ERP studies have investigated predictive processing in second/foreign language sentence comprehension, Moreno et al. (2002) provided evidence for predictive processing in L2. By comparing ERP responses during code-switching in English-Spanish bilinguals, they found that when high-expectancy English words were not encountered or when unexpected Spanish equivalents of high-expectancy words appeared during English sentence reading, larger N400 effects were elicited, accompanied by frontal positivity. These results suggest that L1 conceptual and lexical form prediction mechanisms can extend to L2 processing systems. However, this study examined processing mechanisms during code-switching rather than strict L2 sentence comprehension. Furthermore, if predictive sentence processing is a specialized language-level cognitive mechanism, does it relate to foreign language aptitude —an innate ability that varies across individuals (Wen et al. 2017; Wen 2005)? Therefore, direct research on predictive processing in non-native sentence comprehension is urgently needed.

7. Conclusion

A series of ERP experiments demonstrate that the human brain possesses a cognitive mechanism for predicting upcoming input based on prior contextual information before the input occurs. This prediction operates along two dimensions —semantic-conceptual and lexical form—corresponding to N400 and frontal positivity effects, respectively. Findings from predictive processing research have prompted psycholinguists to refine traditional "semantic-syntactic" dichotomy theories by subdividing conceptual prediction and adding lexical form prediction mechanisms, thereby more comprehensively revealing how a series of cognitive processes unfold through mixed stepwise and parallel modes to achieve sentence comprehension. Further research can explore the linguistic significance of predictive sentence processing, the modality generalizability of prediction mechanisms, their elicitation conditions, and predictive processing patterns across populations with different physiological conditions and language backgrounds. In summary, ERP research on predictive sentence processing has already achieved remarkable results, and future investigations will undoubtedly yield even more groundbreaking discoveries.

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Note: Figure translations are in progress. See original paper for figures.