CORTEX 53 (2014) 9–26

Available online at www.sciencedirect.com

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Research report

Prediction in the service of comprehension: Modulated early brain responses to omitted speech segments

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ARTICLE INFO

Article history:
Received 7 December 2012
Reviewed 13 February 2013
Revised 13 June 2013
Accepted 2 January 2014
Action editor M.J. Tainturier
Published online 15 January 2014

Keywords:
Predictive coding
Semantic expectation
Auditory processing
Omission mismatch negativity (MMN)
Source localization

ABSTRACT

Speech signals are often compromised by disruptions originating from external (e.g., masking noise) or internal (e.g., inaccurate articulation) sources. Speech comprehension thus entails detecting and replacing missing information based on predictive and restorative neural mechanisms. The present study targets predictive mechanisms by investigating the influence of a speech segment's predictability on early, modality-specific electrophysiological responses to this segment's omission. Predictability was manipulated in simple physical terms in a single-word framework (Experiment 1) or in more complex semantic terms in a sentence framework (Experiment 2). In both experiments, final consonants of the German words *Lachs* ([laks], salmon) or *Latz* ([lats], bib) were occasionally omitted, resulting in the syllable *La* ([la], no semantic meaning), while brain responses were measured with multi-channel electroencephalography (EEG). In both experiments, the occasional presentation of the fragment *La* elicited a larger omission response when the final speech segment had been predictable. The omission response occurred ~125 –165 msec after the expected onset of the final segment and showed characteristics of the omission mismatch negativity (MMN), with generators in auditory cortical areas. Suggestive of a general auditory predictive mechanism at work, this main observation was robust against varying source of predictive information or attentional allocation, differing between the two experiments. Source localization further suggested the omission response enhancement by predictability to emerge from left superior temporal gyrus and left angular gyrus in both experiments, with additional experiment-specific contributions. These results are consistent with the existence of predictive coding mechanisms in the central auditory system, and suggestive of the general predictive properties of the auditory system to support spoken word recognition.

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0010-9452/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cortex.2014.01.001

1. Introduction

Utterances are rarely transmitted from the speaker to the listener in an entirely veridical manner. Parts of the speech signal are typically overlaid by external noise originating, for instance, from road traffic or from other speakers. Additionally, the speech signal might be compromised by inaccurate articulation of the speaker. As a consequence, the listener is faced with missing acoustic information that must be compensated to guarantee optimal comprehension. There is general consensus that both predictive and restorative mechanisms play a role in "filling the gaps", yet the underlying mechanisms are far from being understood. Based on electrophysiological recordings, the present paper provides insights into predictive mechanisms involved in the replacement of missing segments in speech comprehension.

In electrophysiological recordings, missing auditory information is often accompanied by elicitation of the omission mismatch negativity (MMN) component of the event-related potential (ERP) (Horváth, Müller, Weise, & Schröger, 2010; Tervaniemi, Saarinen, Paavilainen, Danilova, & Näätänen, 1994; Yabe, Tervaniemi, Reinikainen, & Näätänen, 1997; Yabe et al., 1998). The MMN component reflects the detection of a deviation from expected sensory input (Näätänen, Gaillard, & Mäntysalo, 1978; for reviews, see Garrido, Kilner, Stephan, & Friston, 2009; Kujala, Tervaniemi, & Schröger, 2007; Näätänen, Paavilainen, Rinne, & Alho, 2007; Schröger, 2007; Winkler, 2007). In the case of the omission MMN, the deviation specifically consists of an absence of sensory input at a point in time where a particular auditory stimulus was expected. The advantage of this type of deviation lies in the possibility to unveil the predictive activity of the auditory system, because auditory activity can be observed without any auditory input (Hughes et al., 2001; Raij, McEvoy, Mäkelä, & Hari, 1997). In using this approach, one must ensure that the putative omission-related activity does not simply reflect late indicators of processing previous auditory input (see Bendixen, SanMiguel, & Schröger, 2012, for more detailed discussion). One solution to this problem is to compare conditions with physically identical stimulus history that induce different amounts of predictability of the upcoming (to-be-omitted) auditory stimulus. Any ERP response during the omitted stimulus that is modulated by predictability is likely to reflect signs of predictive processing. Following this logic, predictive activity during silent periods has been shown for tonal material (Bendixen, Schröger, & Winkler, 2009; Janata, 2001; Kraemer, Macrae, Green, & Kelley, 2005; Leaver, Van Lare, Zielinski, Halpern, & Rauschecker, 2009; SanMiguel, Widmann, Bendixen, Trujillo-Barreto, & Schröger, 2013).

For linguistic material, ERP responses similar to the omission MMN have been demonstrated by either omitting or delaying the presentation of a given speech segment, both within repetitive sequences of pseudo-words (Pihko, Leppäsaari, Leppänen, Richardson, & Lyytinen, 1997) and within meaningful sentences (Besson, Faita, Czternasty, & Kutas, 1997; Mattys, Pleydell-Pearce, Melhorn, & Whitecross, 2005; Sivonen, Maess, & Friederici, 2006). Yet as outlined above, the mere elicitation of an omission MMN is not conclusive as to whether the system employed a predictive processing strategy. Besson et al. (1997) additionally manipulated the semantic predictability of the delayed segment by means of cloze probability, but found no effect of this manipulation on the omission-related ERP response (although they noted a weak trend in their data). Likewise, Sivonen, Maess, and Friederici (2006) found no effect of semantic expectedness on early ERP correlates of phoneme obliteration. Mattys et al. (2005) found an early effect of the semantic context in interaction with the uniqueness point in word identification. Two further studies revealed early effects of semantic predictability on the processing of omitted phonemes replaced by external noise (Groppe et al., 2010; Sivonen, Maess, Lattner, & Friederici, 2006). Such early semantic effects on the processing of missing or distorted speech segments have, however, remained elusive, which is consistent with an absence of semantic predictability effects on other types of MMN responses in linguistic material (e.g., Boulenger, Hoen, Jacquier, & Meunier, 2011). The sparse evidence for early effects of semantic predictability contrasts with other approaches revealing convincing evidence in favor of a predictive strategy in language comprehension (e.g., Otten, Nieuwland, & van Berkum, 2007; Vespignani, Canal, Molinaro, Fonda, & Cacciari, 2010; for reviews, see Federmeier, 2007; Van Petten & Luka, 2012). Notably, in most previous studies predictability affected rather late (i.e., after around 400 msec), language-specific ERP components (predominantly the N400 component; for recent reviews, see Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008).

Predictability effects preceding the usual N400 latency have been reported in acoustically intact sentences when strong expectations (arising from high cloze probability) were phonologically or semantically violated by inserting wrong alternatives (e.g., van den Brink, Brown, & Hagoort, 2001; Connolly & Phillips, 1994). Recently, Wang, Zhu, and Bastiaansen (2012) pointed out that for this type of violation, it is not possible to disentangle whether processing relies on prediction or on retrospection (i.e., semantic integration of the unexpected alternative). This ambiguity can be avoided by using acoustic violations (such as missing or distorted speech segments; cf. Strauß, Kotz, & Obleser, 2013) because in this case, no new semantic information is provided; thus processing must rely on prior semantic information.

The present study was designed to investigate the influence of a speech segment's predictability on early, modality-specific electrophysiological responses to this segment's omission. The possibility to obtain such early influences has been demonstrated by Mattys et al. (2005). In order to test for the generality of the obtained effect, we employed two different manipulations of predictability in two experiments with structurally identical material based on the German nouns *Lachs* ([laks]; salmon) and *Latz* ([lats]; bib) differing in their final consonant cluster. In Experiment 1, we employed a simple manipulation of predictability by contrasting the repeated presentation of one of the words (*predictable* segment) with a random alternation between the two words (*unpredictable* segment). In Experiment 2, we employed a complex, natural speech-like form of predictability by embedding the relevant words in a sentence context that either induced a semantic expectation for one of the words

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