International Journal of Psychophysiology 77 (2010) 13–20

Contents lists available at ScienceDirect

International Journal of Psychophysiology

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

Activation and application of an obligatory phonotactic constraint in German during automatic speech processing is revealed by human event-related potentials

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ARTICLE INFO

Article history:
Received 23 December 2009
Received in revised form 24 March 2010
Accepted 29 March 2010
Available online 7 April 2010

Keywords:
Event-related potentials (ERP)
Mismatch Negativity (MMN)
Speech processing
Phonology
Long-term memory
Attention

ABSTRACT

In auditory speech processing, implicit linguistic knowledge is activated and applied on phonetic and segment-related phonological processing level even if the perceived sound sequence is outside the focus of attention. In this study, the effects of language-specific phonotactic restrictions on pre-attentive auditory speech processing were investigated, using the Mismatch Negativity component of the human event-related brain potential. In German grammar, the distribution of the velar and the palatal dorsal fricative is limited by an obligatory phonotactic constraint, Dorsal Fricative Assimilation, which demands that a vowel and a following dorsal fricative must have the same specifications for articulatory backness. For passive oddball stimulation, we used three phonotactically correct VC syllables and one incorrect VC syllable, composed of the vowels [ɛ] and [ɔ] and the fricatives [ç] and [ʃ]. Stimuli were contrasted pairwise in experimental oddball blocks in a way that they differed in regard to their respective vowel but shared the fricative. Additionally to the usual Mismatch Negativity which is attributable to the change of the initial vowel and which was elicited by all deviants, we observed a second negative deflection in the deviant ERP elicited by the phonotactically ill-formed syllable only. This negativity cannot be attributed to any acoustical or phonemic difference between standard and deviant, it rather reflects the effect of a phonotactic evaluation process after both sounds of the syllable were identified. Our finding suggests that implicit phonotactic knowledge is activated and applied even outside the focus of the participants' attention.

1. Introduction

Speech is normally perceived without effort, which requires fast, adaptive, and partly automatic cognitive processes. While phonetic analysis pertains to the processing of continuous acoustic information, phonological processing involves a categorical component, which is attributed to implicit linguistic knowledge represented in long-term memory. Phonological knowledge of a native speaker not only includes the language-specific phoneme inventory, but also abstract principles regulating the co-occurrence of phonemes in sound sequences, i.e. phonotactic restrictions. These aspects of phonological grammar are assumed to be represented independently of the phoneme inventory and to not be included in the entries of the mental lexicon (Kenstowicz, 1994; de Lacy, 2007).

In speech processing, the system rapidly accesses phonetic as well as phonological information. On this processing level, by hypothesis, the system does not require a conscious effort, but operates pre-attentively, that is, without active attentional selection (e.g., Schröger et al., 2004). In cognitive neuroscience, an important research interest deals with the question, to what extent speech processing takes place pre-attentively in this way (for a review, see Pulvermüller and Shtyrov, 2006).

In the present study, we investigated whether or not language-specific phonotactic knowledge is activated and applied pre-attentively. To this end, we used the Mismatch Negativity (MMN) ERP component as a probe. MMN is regarded to be an automatic brain response in the moderated sense that it can be elicited even in the absence of attention. However, MMN is known to be sensitive to modulations by top-down processes such as attention (e.g., Schröger, 1998). Predominantly, it is presumed to reflect a pre-attentive auditory sensory-memory-based deviance detection mechanism (e.g., Näätänen et al., 2007). MMN is elicited by infrequent acoustic stimuli (so-called deviants), which occasionally occur among frequently repeated standard stimuli. Because this deviance detection mechanism operates non-volitionally, the MMN can be used to investigate what regularities are detected when sounds are not in the

Abbreviations: ANOVA, Analysis of variance; DFA, Dorsal fricative assimilation; EEG, Electroencephalogram; EOG, Electrooculogram; ERP, Event-related potential; MMN, Mismatch negativity; MMNm, Magnetic mismatch negativity.

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doi:10.1016/j.ijpsycho.2010.03.011

focus of attention. Moreover, MMN has been shown to be sensitive to contents of long-term memory such as linguistic knowledge. In this vein, MMN has been shown to be sensitive to accessing phonetic as well as segment-related phonological information (Näätänen et al., 1997; Dehaene-Lambertz, 1997; Sharma and Dorman, 2000; Winkler et al., 1999; Phillips et al., 2000; Eulitz and Lahiri, 2004; for a review, see Näätänen et al., 2007; Shtyrov and Pulvermüller, 2007).

As for the level of phonotactic knowledge, protocols using MMN and its magnetic equivalent, MMNm, have been applied to demonstrate processing effects of appropriate and inappropriate nasal place assimilation (Mitterer and Blomert, 2003; Tavabi et al., 2009) and distributional probabilities of phoneme clusters (Bonte et al., 2005, 2007). Using an active experimental protocol, Dehaene-Lambertz et al. (2000) showed spontaneous repair of attended syllable structure violations in Japanese (see also Flagg et al., 2006, for MEG effects of violated nasal assimilations).

In a previous MMN study (Steinberg et al., in press) we investigated the influence of an obligatory phonotactic restriction in German grammar on pre-attentive speech processing using ill-formed speech material. Concretely, we focused on Dorsal Fricative Assimilation (DFA), an obligatory phonotactic restriction in German (for phonological analysis of the phenomenon, see Hall, 1989, 1992; MacFarland and Pierrehumbert, 1991; Merchant, 1996; Noske, 1997; Féry, 2001). DFA demands that a vowel and a following dorsal fricative (the palatal [ç] or the velar [x]) must agree in their phonological specifications for tongue backness (Féry, 2001). After front vowels, there occurs [ç], as for example [ɛçt] (*echt*, "real"). After back vowels, there occurs [x], like in [kɔx] (*Koch*, "cook"). Ill-formed sequences consisting of a front vowel followed by the velar fricative such as *[ɛx] were found to elicit additional MMN because of violating the constraint of Dorsal Fricative Assimilation. However, we showed this phonotactic effect by means of one ill-formed syllable type only. Potentially, specific properties of the employed stimulus syllables may have had an impact on the observed effect. Especially, since this type of DFA violation is phonotactically well-formed both in Dutch and in Swiss Standard German (e.g., "bad", German *schlecht* [ʃlɛçt], Dutch *slecht* [slɛxt], Swiss Standard German *schlecht* [ʃlæxt]), potential confounds with passive experience in these languages, although highly unlikely, could not be entirely ruled out. Therefore, further research is desirable to provide modified replications of our previous findings by expanding the investigation to several kinds of phonotactic violation.

In the present study we investigate the other possible type of violation of DFA, an inappropriate combination of a back vowel and a following palatal fricative such as *[ɔç]. Using a passive oddball protocol, we tested whether and to what extent this violation of DFA affects pre-attentive speech processing by comparing the MMN response to phonotactically ill-formed stimuli (*[ɔç]) with the MMN response to well-formed stimuli ([ɛʃ] as in German "fesch", *smart*, [ɛç] as in German "echt", *real*, [ɔʃ] as in German "Frosch", *frog*). These syllables were contrasted pairwise in oddball blocks so that they differ with regard to the vowel, while sharing the fricative (see Fig. 1). Therefore, in oddball blocks, acoustical stimulus deviation occurred only at stimulus onset. For all syllables, we predicted MMN responses elicited by the change of the initial vowel, as has repeatedly been reported. In addition, we only expected the ill-formed deviant to elicit an additional negative-going ERP effect after the fricative being processed, reflecting pre-attentive activation and application of the obligatory phonotactic constraint DFA.

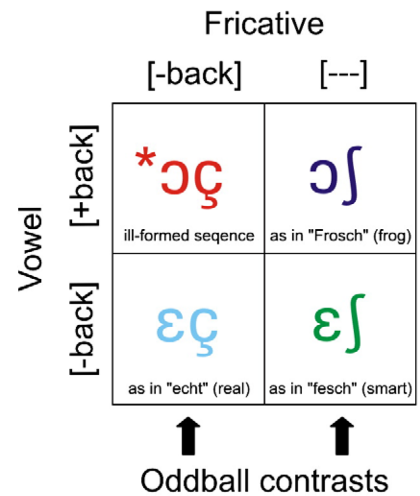

Fig. 1. Experimental design depicted as a two by two table. The rows represent the back and the front vowel with their respective specifications of the phonological place feature [±back]. The columns differentiate the palatal and the coronal fricative, the latter not participating in DFA (agreement for backness) and unspecified for this feature by assumption.

2. Materials and methods

2.1. Participants

Sixteen volunteers participated in the study (eight male; median age 25 years; range 19–30; two left handed) and were included in the analysis, all of them monolingual native speakers of German. Handedness was assessed using an inventory adopted from Oldfield (1971). All participants reported normal auditory and normal or corrected-to-normal visual acuity and no neurological, psychiatric, or other medical problems. They gave informed written consent and received monetary compensation. Due to technical problems, the data of two additional participants had to be excluded from further analysis. Because the experimental blocks were counterbalanced for a total of sixteen participants, the data of yet two other participants were collected unnecessarily and were excluded from the eventual analysis as well. The study conforms with The Code of Ethics of the World Medical Association (1964, Declaration of Helsinki).

2.2. Materials

Four vowel–consonant (VC) syllables were used as stimulus categories (types): [ɛʃ], [ɛç], [ɔʃ], and *[ɔç]. None of these syllables has lexical meaning in German. The stimuli are phonotactically well-formed in German, except for the syllable *[ɔç], which violates the constraint Dorsal Fricative Assimilation (see Fig. 1). In contrast to [ɛç] and *[ɔç], the syllables containing the coronal sibilant [ʃ] do not participate in DFA because this constraint only applies to the dorsal fricatives [ç] and [x] (Hall, 1992; Féry, 2001). The phonemes were selected on the basis of the following criteria: Firstly, for reasons of comparability, the vowels and the fricatives, respectively, were supposed to share as much phonetic and phonological properties as possible. [ɛ] and [ɔ] feature the same approximate height of tongue in articulation as well as the property of articulatory laxness; phonologically they share the features [-high], [-low] and [-tense]. The fricatives [ç] and [ʃ] are both voiceless and have similar (palatal, palato-alveolar) places of articulation, [ʃ] not being specified for backness (Hall, 1992). Secondly, the sounds should differ in a sufficient manner, so that confusion is impossible. The fricatives clearly differ with respect to their spectral properties, as do the vowels, and thus a compensation of the ill-formed sequence *[ɔç] to [ɔʃ] or to [ɛç] is highly unlikely.

Stimulus material was digitally recorded with a 48 kHz sampling rate on a portable recorder. The syllables were articulated numerous times by a professional female speaker of German. We have decided to use naturally spoken speech material rather than synthetic material in order to avoid the risk of getting incoherent brain responses because of misleading phonetic properties, or due to a basic unnaturalness of the signal. However, our design requires the articulation of a sound