First publ. in: Brain Research ; 1394 (2011). - pp. 79-89

Research Report

"What you encode is not necessarily what you store": Evidence for sparse feature representations from mismatch negativity

Sonia A. Cornell[a], *Aditi Lahiri*[b], *Carsten Eulitz*[a,*]

[a]*Department of Linguistics, University of Konstanz, Germany*
[b]*Department of Linguistics, Philology and Phonetics, University of Oxford, UK*

ABSTRACT

The present study examines whether vowels embedded in complex stimuli may possess underspecified representations in the mental lexicon. The second goal was to assess the possible interference of the lexical status of stimuli under study. Minimal pairs of German nouns differing only in the stressed vowels [e], [ø], and [o], and derived pseudowords, were used to measure the Mismatch Negativity (MMN) in a passive oddball-paradigm. The differing vowels were chosen such that the place of articulation information was conflicting vs. non-conflicting in the framework of models assuming underspecified representations in the mental lexicon (i.e. minimizing featural information by omitting redundant information in order to ensure efficient speech processing), whereas models assuming fully specified phonological representations would predict equal levels of conflict in all possible contrasts. The observed pattern of MMN amplitude differences was in accordance to predictions of models assuming underspecified phonological representations. As the possible interferences by other levels of linguistic processing was demonstrated, it seems favorable to use pseudowords for investigating phonological effects by means of MMN.

1. Introduction

One issue in neurolinguistics is the question of the precise nature of mental representations involved in speech processing. This touches on the problem of how the brain copes with the enormous variations in speech. Acoustically, one and the same segment may vary across speakers, contexts, speaking rate and many other factors. Nevertheless, listeners handle this variation in the signal with ease. The nature of linguistic representations, as widely discussed in the literature (Poeppel et al., 2008; Stevens, 2002; Stevens and Keyser, 2010; for a review see Klatt, 1989; McQueen, 2005), is one important element. Different psycholinguistic models have very different views on the nature of mental representations. Based on the resolution of variability, we can distinguish perhaps three types of models. The first type assumes that lexical entries are made up of very detailed memories based on the experiences of the native speaker (Bybee, 2001; Johnson, 1997). The second type highlights the active process of compensation for the variability in speech, rather than the organization through detailed representations (Gaskell, 2003; Gaskell and Marslen-Wilson, 1996, 1998; Gaskell and Snoeren, 2008). The third type of model assumes that the speech signal is transformed into abstract features which in turn serve to match abstract lexical representations (Connine et al., 1993, 1997; Connine and Pinnow, 2006; Fitzpatrick and Wheeldon, 2000; Lahiri and Marslen-Wilson, 1991; Marslen-Wilson et al., 1995; Wheeldon and Waksler, 2004). The featurally underspecified lexicon model (FUL; (Lahiri and Reetz, 2002, 2010)), is one example of abstract approaches to lexical representations. It claims that there is only one single underlying representation for each morpheme stored in the lexicon. Detailed phonetic or predictable phonological information is not stored.

Resolving variation is possible in abstractionist models like FUL (Lahiri and Reetz, 2002, 2010) due to representations where not all phonological features are stored. There is a considerable amount of literature reporting behavioral and neurophysiological evidence for the underspecification of [CORONAL] place of articulation in perception and production (e.g. Eulitz and Lahiri, 2004; Friedrich et al., 2006, 2008; Gumnior et al., 2005; Lahiri and Reetz, 2002, 2010; Walter and Hacquard, 2004; Wheeldon and Waksler, 2004; Zimmerer et al., 2009). However, as mentioned before this issue is still controversially discussed (Gaskell and Marslen-Wilson, 1996, 1998; Gaskell and Snoeren, 2008; Gow, 2002; Mitterer, 2003; Mitterer and Blomert, 2003; Tavabi et al., 2009).

In the present study we distanced ourselves from any possible contextual influences, and focus on [e], [ø], and [o] focuses on vowel alterations. These alterations were not served by assimilations — they are distinct vowels in German. In an earlier study, Eulitz and Lahiri (2004) examined isolated vowels also free of context. However, although isolated vowel sounds can form lexical items (e.g. English [ai] "I", Dutch [y] "you — honorific", Bengali [o] "he/she"), they are few in number. To examine whether such vowel alterations behave in the same way in disyllabic complex structures, we compared them in pairs of words and pseudowords.

In this paper we study the possibility of underspecified phonological representations by using the Mismatch Negativity (MMN). The MMN, a component of the event-related brain activity, is an automatic change detection response in the brain even outside the focus of attention. The MMN can be elicited by memory-mismatches, i.e. when an acoustic event deviates from a memory record describing the immediate past of a sound sequence heard, as well as regularity-violations, i.e. the violation of rules extracted from regular inter-sound relationships which are mapped to the concrete sound sequence by detailed auditory sensory information (Näätänen, 1992; Näätänen et al., 1978; Schröger, 1996, 1998; Winkler et al., 1996, for a review; Näätänen and Winkler, 1999; Winkler, 2007). Furthermore, the MMN has been suggested to reflect long-term memory traces for language sounds such as phonemes (Dehaene-Lambertz, 1997; Näätänen, 2001; Näätänen et al., 1997), syllables (Shtyrov et al., 2000) and lexical representations of words (e.g. Endrass et al., 2004; Jacobsen et al., 2004; Pettigrew et al., 2004; Pulvermüller et al., 2001, 2004; Shtyrov et al., 2008; for review see Näätänen et al., 2007; Pulvermüller and Shtyrov, 2006; Shtyrov and Pulvermüller, 2007). Reliable MMNs can be obtained in the oddball paradigm, by presenting the subject with occasional mismatching infrequent, deviant stimuli after a series of identical, standard stimuli. It appears as a negative deflection from the onset of the deviation around 100–250 ms at fronto-central electrode sites usually appearing with reversed (positive) polarity at electrodes positioned over the opposite side of the Sylvian fissure along the mastoids (Schröger, 1998).

Extending the argument to phoneme perception, it has been proposed that the sound percept, created by the deviant stimulus corresponds to the surface representation, formed by phonological features extracted from the acoustic signal. The series of standard stimuli presented before the deviant, forms a central sound representation where the information structure is closer to the format used for long term memory (e.g. Cowan et al., 1993; Näätänen et al., 1993), i.e. close to the underlying representation in the mental lexicon. Thus, the change detection response reflects — besides the acoustic change — the contrast between the surface and the underlying representation (Eulitz and Lahiri, 2004).

The nature of mental representations of phonological features tapped onto by means of the MMN has previously been studied for vowels in isolation (Eulitz and Lahiri, 2004). Eulitz and Lahiri (2004) used the same three vowels [e], [ø], and [o] as in our present study, the phonological place features of which extracted from the signal are [DORSAL] for [o], and [CORONAL] for [e] and [ø]. It is important to note, that the acoustic information of the F2 and F3 formant frequency differences of [e] and [ø] are equidistant to that of the difference of [o] and [ø]. However, the phonological place feature of [o] differs from the phonological place features of [e] and [ø] that share the same place feature (see Experimental procedures section). Following the FUL-model, when [e] and [ø] are presented as deviants after the participant has heard a row of /o/ as standard stimuli such that [DORSAL] is pre-activated, a phonological conflict occurs, since [CORONAL] is extracted from the deviant which does not match [DORSAL]. In contrast, if the standards and deviants are reversed, i.e. /ø/ and /e/ as standards are followed by [o] as deviant, then no conflict is expected since /ø/ and /e/ as coronals are underspecified for place in the mental lexicon. Eulitz and Lahiri's (2004) crucial result was the following: The same acoustic contrasts triggered asymmetric MMNs when they were reversed as standard and deviant in the coronal–dorsal contrast. Earlier latency and higher amplitude MMN values were found for the coronal vowel deviants [e] and [Ø], when [DORSAL] was pre-activated by the standard /o/, and smaller values for the reversed case, with the coronal vowels serving as standards. However, the coronal vowel contrast [e] and [Ø] did not differ in amplitude or latency independent of whether they served as standard or deviant. These differential MMN asymmetries for similar acoustic/phonetic differences between pairs of vowels in isolation were discussed as a reflection of the brain referring to underspecified phonological representations.

The aim of the current study is to extend the reported study by the following aspects. First, we examined medial vowel alterations in word and pseudoword pairs to find out whether vowels in medial positions in complex linguistic structures reliably evoke MMN effects similar to vowels in isolation. The second issue concerns the possible interactive effects of the lexical status of the stimuli with the phonological level of feature conflicts.

With respect to the first goal, phonological models assuming full specification (Bybee, 2001; Gaskell and Marslen-Wilson, 1996, 1998) would expect to find equal MMNs between all contrasting vowels placed in words and pseudowords, independent of the direction of presentation of the standard and deviant. As mentioned before, only models presuming underspecification of phonological features predict an asymmetry of MMNs within the reversal of vowel contrasts (pairs of inversion), presented as standard and deviant (for summary see Table 1). As in Eulitz and Lahiri (2004), we expected to find higher MMN amplitudes of our vowel contrast if the place feature [CORONAL] extracted from the deviant [Ø] maps onto the place feature [DORSAL] in the mental representation created by the standard /o/, which is assumed to be a conflict (conflicting pair). In the reversed comparison when the feature [DORSAL] from the deviant [o] maps onto the underspecified representation of the standard /Ø/ with no information about the place of articulation a non-conflict (non-conflicting pair) occurs and smaller MMNs are expected. Thus, in this acoustic/phonetic contrast $[o]_{/ø/}$ vs. $[Ø]_{/o/}$ (labeling see Table 1) an asymmetric MMN pattern would be expected. For our control condition contrasts [Ø] and [e] we do not predict asymmetric MMNs, since the feature [CORONAL] is extracted from the acoustic signal of the deviant in both vowels and does not conflict with the underlying representation that is created by the corresponding underspecified standard (equally non-conflicting pair of inversion). Note, that for reasons of clarity we restrict the asymmetry predictions to effects driven by phonological processes, i.e. different levels of conflict due to compatibility problems at the level of phonological features. We are aware of the fact that asymmetric MMN effects can be elicited by sound features on the acoustic, or the phonetic levels of processing as shown in Bishop et al. (2005) or Jacobsen (2004). However, given that we have two pairs of inversion symmetric with respect to the acoustic/phonetic contrasts and, moreover, both pairs are not equal but relatively close to each other in format space, we argue in favor of phonological effects for the following reason. In a situation where one pair of inversion shows symmetric MMNs and the other one asymmetric MMN, an additional MMN effect originating from other levels of processing must have been superimposed in one but not the other pair of inversion. At least for the pseudoword conditions, there are good reasons that superimposed MMN effects stem from the phonological level of processing.

With respect to the second issue, i.e. the possible interaction of phonology and lexicality, a number of studies have shown that the MMN is influenced by lexical status (Endrass et al., 2004; Pettigrew et al., 2004; Pulvermüller et al., 2001, 2004; Shtyrov and Pulvermüller, 2002, 2007; Shtyrov et al., 2008; Yasin, 2007; for alternative views see also Jacobsen et al., 2004). Words seem to evoke a larger MMN-amplitude in a pseudoword context (created by standards) compared to pseudowords in a word context. On the other hand, studies of phonological processing can be more complicated when other lexical information may interfere. In certain cases it is even impossible to control for all potential confounds coming from the semantic or syntactic level of processing. To demonstrate whether non-words can be used to study phonological representations or may even be better to do so, we compared the processing of the same phonological contrasts in both a word and a pseudoword condition. But, contrary to the above mentioned studies we did not have word–pseudoword sequences in one block to study lexicality effects on the MMN rather we compared our phonological contrasts within two blocks — one that only contained real words and one exclusively with pseudowords. The idea was to check out a strategy to investigate phonological processing with less interference from other sources of linguistic knowledge.

2. Results

A clear MMN in the time window of 200–350 ms, i.e. 100–250 ms after change onset, was observed in all experimental conditions. Fig. 3 illustrates the MMN effect for a sample phonetic contrast ($[ø]_{/o/}$) for words and pseudowords using 9 electrode positions. A clear polarity reversal of midline electrodes relative to the mastoids can be obtained.

Fig. 4 gives an overview of MMN waveforms for all experimental conditions (re-referenced against linked mastoids). Note the more pronounced MMN difference between conflicting and non-conflicting contrasts (right hand column) relative to the contrasts without featural conflicts for both, the words and the pseudowords. Moreover, there is an interference of lexical status seen for the pairs of inversion without feature conflicts. Whereas the $[e]_{/ø/}$ contrast shows similar MMN amplitudes for words and pseudowords, the $[ø]_{/e/}$ contrast is larger in amplitude for words compared to pseudowords. A summary of these MMN amplitude difference is given in Fig. 5.

Statistical analyses (paired *t*-tests comparing standard and deviant waveforms separately for each experimental condition) ensured that MMNs were obtained for all experimental conditions (*words*: $[e]_{/ø/}$: mean amplitude = −1.724; t (18) =

Table 1 – Predictions about the amount of conflict for the vowel contrasts of models assuming full specification and underspecification (i.e. no specification of the coronal place of articulation in the underlying representation), correspondingly. PW = pseudowords.

Experimental conditions for words and pw $[Deviant]_{/Standard/}$	Place feature in the surface representation (extracted by the deviant)	Place feature in the underlying representation (activated by the standard)	Hypothesis full specification	Hypothesis underspecification
$[ø]_{/o/}$	**[CORONAL]**	**[Dorsal]**	**Conflict**	**Conflict with [DORSAL]**
$[o]_{/ø/}$	[DORSAL]	[ ]	Conflict	Non-conflict with [ ]
$[ø]_{/e/}$	[CORONAL]	[ ]	Conflict	Non-conflict with [ ]
$[e]_{/ø/}$	[CORONAL]	[ ]	Conflict	Non-conflict with [ ]

The underlying gray area highlights the only critical "conflicting" condition $[ø]_{/o/}$ for the model assuming underspecification. Note, that the predictions are the same for the word and the pseudoword (pw) conditions.

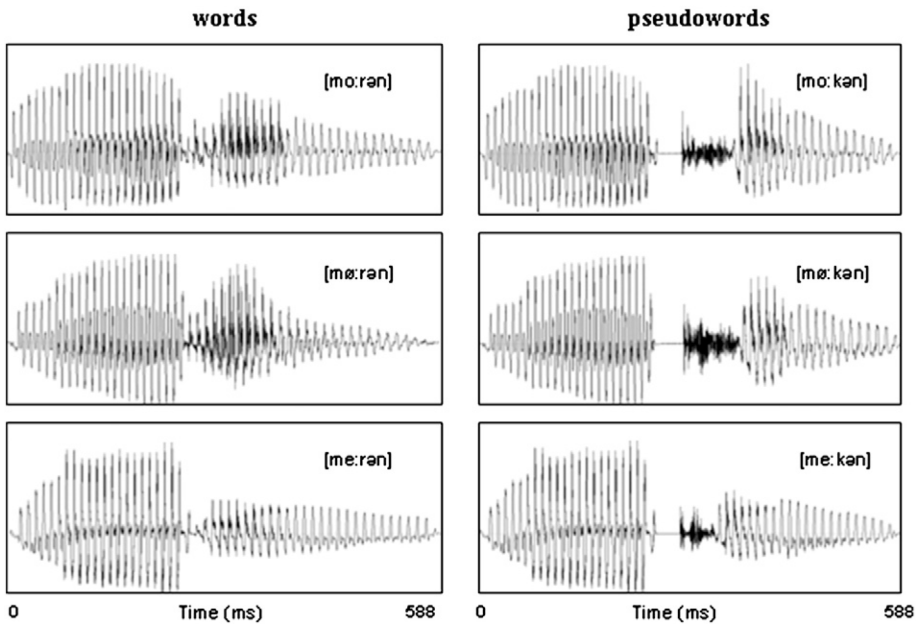

Fig. 1 – Oscillograms of acoustic stimuli used in the experiment: words: [mo:rən], [mø:rən], and [me:rən] and pseudowords: [mo:kən], [mø:kən], and [me:kən]. The standard and deviant stimuli were maximally matched for their acoustic properties in all conditions.

−6.394; [ø]$_{/e/}$: mean amplitude = −2.332; t (18) = −6.646; [ø]$_{/o/}$: mean amplitude = −2.222; t (18) = −6.241; and [o]$_{/ø/}$: mean amplitude = −0.889; t (18) = −3.414; *pseudowords*: [e]$_{/ø/}$: mean amplitude = −1.826; t (15) = −5.544; [ø]$_{/e/}$: mean amplitude = −1.420; t (18) = −3.831; [ø]$_{/o/}$: mean amplitude = −2.149; t (18) = −11.156; and [o]$_{/ø/}$: mean amplitude = −1.160; t (18) = −4.376; all p-values < 0.003).

The overall ANOVA including the repeated measures factors Wordness (words vs. pseudowords), Pair of Inversion showing an equalized acoustic change (non-conflicting pair [e]$_{/ø/}$ vs. [ø]$_{/e/}$ vs. conflicting pair [ø]$_{/o/}$ vs. [o]$_{/ø/}$) and Direction of Acoustic Change of the F2 formant frequency between the deviant and standard (F2 falling: [ø]$_{/e/}$ vs. [o]$_{/ø/}$ vs. F2 rising:

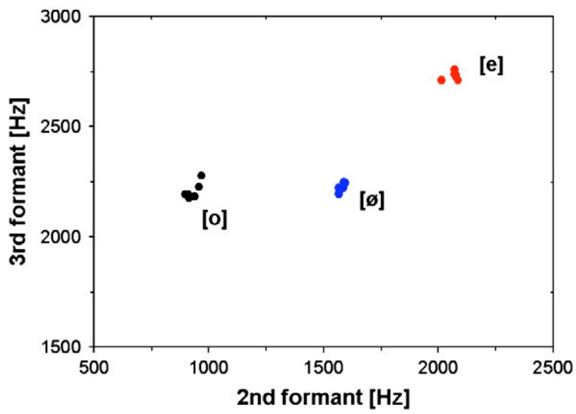

Fig. 2 – Acoustic characteristics of the three natural vowel categories used in the study. There are six exemplars of each vowel category. All vowels show their locations in the F2–F3 space. Note, that the distances between [e] and [ø] are similar to [o] and [ø].

[e]$_{/ø/}$ vs. [ø]$_{/o/}$) revealed a three-way interaction, (F (1, 18) = 4.777; p = 0.042), indicating that on top of the more pronounced MMN difference between conflicting and non-conflicting contrasts relative to the contrasts without featural conflicts an interference of lexical status can be obtained.

To describe the effects of phonetic contrasts for acoustically equalized conditions in more detail, paired comparisons were calculated for all pairs of inversions. For both, words and pseudowords, significant differences between the [ø]$_{/o/}$ contrasts (containing the phonological conflict) and the [o]$_{/ø/}$ contrasts (the non-conflicting condition) were found (words: (F (1, 18) = 8.946; p < 0.008)); pseudowords: (F (1, 18) = 10.943; p < 0.004). However, the [e]$_{/ø/}$ vs. [ø]$_{/e/}$ contrasts, i.e. the pairs of inversion without phonological conflicts, did not differ significantly (words: F (1, 18) = 2.679); pseudowords: (F (1, 18) = 1.626; all p-values > 0.1).

To localize the interference effect of lexicality, paired comparisons between words and pseudowords were calculated for each phonetic contrast. A significant difference was found for the [ø]$_{/e/}$ contrast only (F (1, 18) = 4.991; p < 0.038). No further differences were found between words and pseudowords ([e]$_{/ø/}$: F (1, 18) = 0.071; [ø]$_{/o/}$: F (1, 18) = 0.040; and [o]$_{/ø/}$: F (1, 18) = 0.885; all p > 0.3). That is, words and pseudowords showed an equal pattern of results for the conflicting as well as most of the non-conflicting contrasts. Only one non-conflicting condition ([ø]$_{/e/}$) seems to be affected by lexicality.

3. Discussion

The present MMN study was designed (1) to examine whether the underspecification of the [CORONAL] place of articulation that has been demonstrated in isolated vowels (Eulitz and Lahiri, 2004) can be shown for linguistically more complex

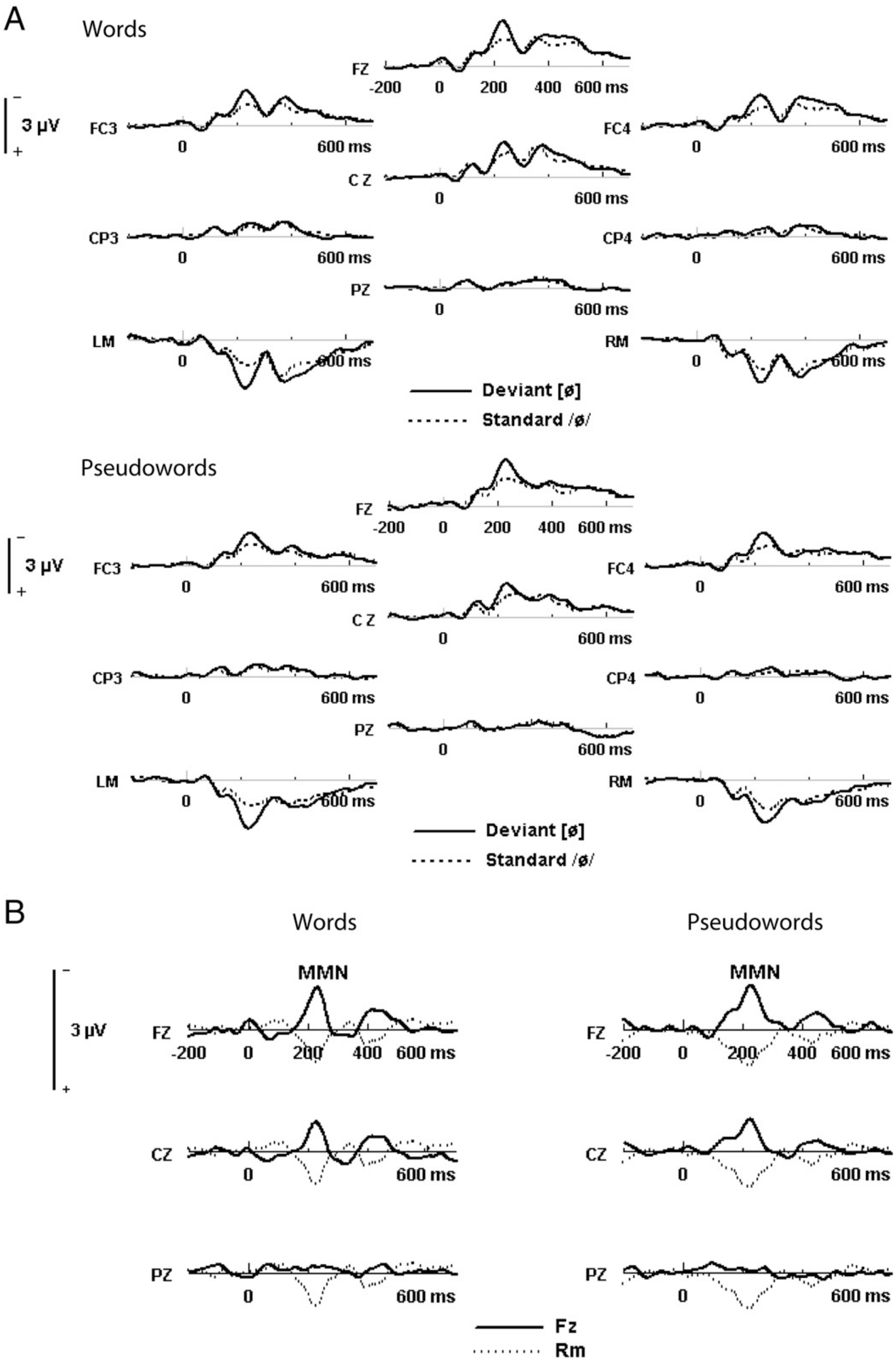

Fig. 3 – Grand-average waveforms for the conflicting condition [ø]/o/ for words and pseudowords. Panel (A) plots the ERPs of standard (dashed line) and deviant (solid line) waveforms for 9 electrode positions (average referenced), midline (Fz, Cz, and Pz), left and right fronto-central electrodes (FC3, FC4, CP3, and CP4), as well as left and right mastoid electrodes (Lm and Rm) showing the MMN typical polarity reversal for words (upper part) and pseudowords (lower part). Panel (B) plots the MMN difference waveforms for words and pseudowords for the three midline electrodes Fz, Cz, and Pz (solid line) against Rm (dotted line). Note, that the MMN is the difference of the same sound used as a standard in one and as a deviant in another experimental block.

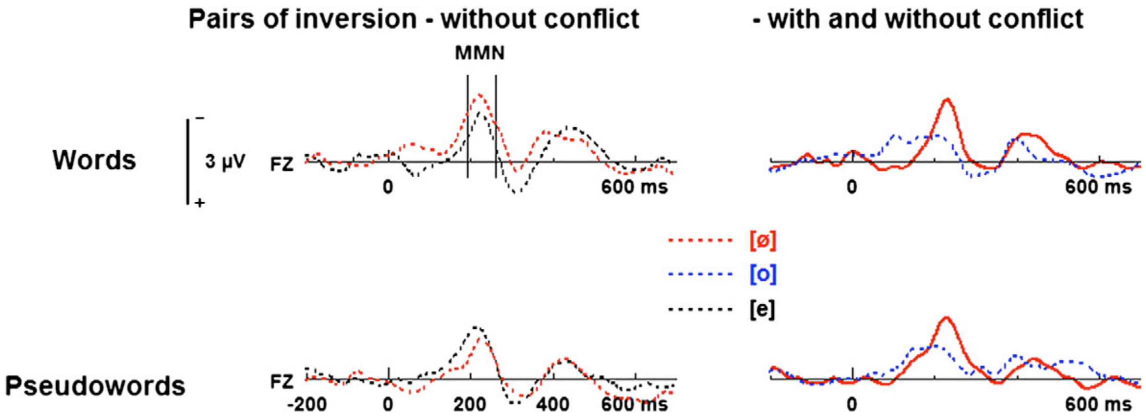

Fig. 4 – Grand-average waveforms of the frontal electrode position (Fz; re-referenced against linked mastoids) for the non-conflicting Pair of Inversion ($[ø]_{/e/}$ vs. $[e]_{/ø/}$) and the Pair of Inversion with and without conflict ($[ø]_{/o/}$ vs. $[o]_{/ø/}$) for words (above) and pseudowords (below). The color of the waveforms codes the deviant vowel, red for [ø], blue for [o], and black for [e]. All non-conflicting conditions are shown as dotted lines; the conflicting condition ($[ø]_{/o/}$) is solid.

language processing conditions in word medial position and (2) to assess the possible interference of the lexical status of stimuli under study. Our results showed that when embedded in linguistically more complex stimuli, such as words or matched pseudowords, the vowel contrasts provided supporting evidence for the underspecification of the [CORONAL] place of articulation in vowels. This conclusion is based on the fact that we found larger MMN amplitudes whenever a place-of-articulation conflict occurred compared to non-conflicting situations (Eulitz and Lahiri, 2004). According to the FUL-model (Lahiri and Reetz, 2002, 2010), a phonological conflict occurs in this experiment, when the deviant is the coronal [ø] and the standard stimuli the dorsal vowel [o]. When the deviant is heard, the information about the coronal place of articulation is extracted from the signal after the subjects hear a row of standard stimuli [o], which have pre-activated a [DORSAL] place of articulation creating a conflict. No conflict occurs when [o] is the deviant and /ø/ the standard. Alternative models assuming fully specified place of articulation information (Bybee, 2001; Gaskell, 2003; Gaskell and Marslen-Wilson, 1996, 1998; Johnson, 1997) would predict a similar phonological conflict for both directions of acoustic change, i.e. predict main effects but no significant interaction of Pair of Inversion and Direction of Acoustic Change. Thus, our significant two-way interaction is clearly in line with the predictions of the FUL-model and cannot be explained by a model that fully specifies place-of-articulation information which would predict at best two main effects in the present experimental setup (for a summary of the predictions see also Table 1).

Context may, however, produce asymmetric effects. Gaskell's context-sensitive, experience-driven connectionist model (Gaskell, 2003) would predict asymmetries under different phonological environments. With respect to the present experiment, Gaskell's model cannot really explain our asymmetries since our stimuli are built in the way that all varying vowels have the same preceding (/m/) and following contexts (for words /r/, for pseudowords /k/), therefore no influencing context information between the conditions can come from adjacent segments, or contextual assimilations.

With respect to the present results among the discussed parameters, a possible influence of phonotactic probabilities might be of relevance. Bonte et al. (2005) reported higher MMN amplitudes for non-words with high phonotactic probability (*notsel*) as compared to nonwords with low probability (*notkel*). The distributional probabilities of C[V]C sequences in our experiment were highest for stimuli with an [e] and lowest for stimuli with an [ø]. Thus the findings of Bonte et al. (2005) would predict a higher MMN amplitude for [me:kən] and [me:rən] compared to all the [ø] and [o] conditions. However, the pattern of MMN differences in the present study does not follow these predictions. The conditions with the largest divergence in the phonotactic probabilities showed no MMN differences whereas the conditions with a just moderate difference in phonotactic probabilities showed a reversed MMN difference, i.e. contrary to Bonte et al. (2005), we found larger MMN amplitudes for the low phonotactic probability conditions. Is there a possible common ground of both studies to explain the differential pattern of the reported MMN effects? From a phonological point of view, Bonte et al. (2005) used both place-of-articulation and manner-of-articulation differences in consonants to create a contrast between standard and deviant. At a featural level, the *notsel–notkel* difference includes a manner change (from [STRIDENT] to [PLOSIVE]) as well as a place change (from [CORONAL] to [DORSAL]). Given the underspecification of the [CORONAL] place of articulation (e.g. Friedrich et al., 2006, 2008; Lahiri and Reetz, 2002, 2010) and the findings about the correlation of levels of feature conflicts with the MMN amplitude in the present study as well as in Eulitz and Lahiri (2004), the MMN asymmetries in Bonte et al. (2005) could be interpreted as a reflection of the underspecified [CORONAL] place of articulation in *notsel*. With respect to the contrasts of place features, the stimuli used in Bonte et al. (2005) follow the same systematic pattern of alternations as described in Table 1 for the present experiment since the place of articulation is [CORONAL] for both [ø] and [s], and [DORSAL] for [o] and [k]. In sum, in the light of the

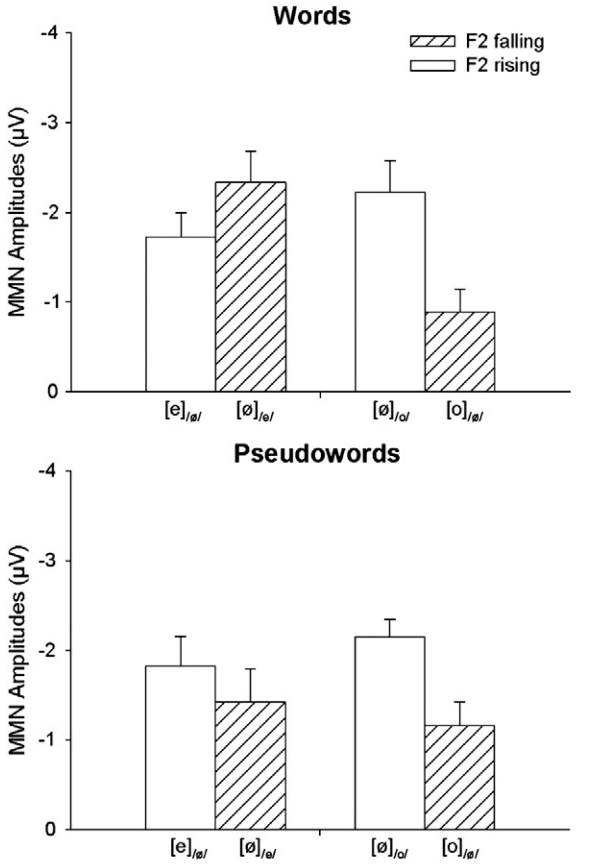

Fig. 5 – Mean MMN amplitudes of the conflicting and all non-conflicting conditions for words (above) and pseudowords (below). The non-conflicting Pair of Inversion ($[ø]_{/e/}$ vs. $[e]_{/ø/}$) is shown on the left hand part and the Pair of Inversion with and without conflict ($[ø]_{/o/}$ vs. $[o]_{/ø/}$) on the right. Properties of the bars indicate the Direction of Acoustic Change (striped for F2 formant falling, and white for F2 rising). Note the more pronounced amplitude difference for the Pair of Inversion which includes the phonological conflict $[ø]_{/o/}$ for both words and pseudowords. Error bars show the standard error of the mean (SEM).

results of the present experiment where the phonotactic probabilities were calculated on the basis of those proposed by Bonte et al. (2005), we have no supporting evidence for the influence of phonotactic probabilities as suggested them. Taken all the results together, however, there is a hint that the MMN effects in Bonte et al. (2005) might have been driven by differential conflict levels between phonological features in the same way as in the present study, similar to that of Eulitz and Lahiri (2004). If this is indeed the case, Bonte et al. (2005) would be one of the first studies (together with Walter and Hacquard, 2004) which suggest a generalization of the original results for vowels to consonantal speech sounds. Further research is, however, necessary to study these aspects in a controlled fashion.

A second goal of the study was to explore possible inferences of other levels of linguistic processing with the perception of phonological contrasts and its impact on the MMN effects. Consequently, blocks of real words and matched pseudowords were presented. The stimuli were designed in a way that the final syllable (offset of the crucial vowel) could complete either a word or a pseudoword. It is important to note, that up to the end of the first syllable (CV-syllable) the processing system could not have received full information about the lexical status. The point at which the lexical status comes to play is after the critical vowel, but it is the critical vowel that elicited the MMN response.

The three-way interaction of Wordness, Pair of Inversion and Direction of Acoustic Change showed that the MMN difference pattern between the word and pseudoword conditions was differently pronounced in a different way for the various phonetic contrasts. With respect to the second goal of our study, this shows that interferences of the lexical level of processing are feasible and have to be taken into account for such experiments. To avoid possible effects of lexical ambiguities we suggested using pseudowords as stimuli in studies of phonological effects whenever possible. One might argue that pseudowords do not tap into lexical representations at all and that the pseudoword standards do not activate mental representations. However in order to decide whether the incoming speech sounds make up a word or pseudoword the lexicon must be activated, thus activating the same features independent of the lexical status. Connine et al. (1993) argues that words and similar-sounding nonwords are not treated equivalently. In her studies she finds priming effects for derived words (nonwords that are minimally changed in one or two features) that are reduced to those for words. However, she concludes that the lexical item activated in memory is simply the best hypothesis available for the acoustic input, thus tapping into the same lexical items independent of the lexical status. One might conclude that it does make sense to use pseudowords when investigating lexical representations.

Post-hoc tests attributed the effect of Wordness to the $[ø]_{/e/}$ contrast. This cannot be a wordness effect in general (i.e. visible for all contrasts under study), but just one condition that appeared for reasons we cannot fully explain and which needs further investigation. As mentioned in the Experimental procedures section our words could not be fully controlled. The words in isolation could have a different meaning or case for some but not all words or even being interpreted as a verb. Although we made sure in the instructions that the ambiguity was minimized and the words were repeated many times in the blocks this kind of superimposition might have taken place. Remarkably, in terms of possible ambiguities [møːrən] is the least problematic item in the present study. It has just one possible lexical source and no word class ambiguities can be induced when listening to that word in isolation. Unfortunately, it can be the nominative or dative plural of the same word but this holds for [meːrən] as well, where no MMN difference between the word and pseudoword condition can be found. Perhaps one explanation to account for this difference between [møːrən] and the others lies in their lexical syllable structures. The surface forms were perfectly controlled in terms of the syllabic and segmental structures. Two of them, [meːr] and [moːr] have monosyllabic morphemes while [møːrə] is underlyingly disyllabic. And as we mentioned earlier, all the words are inflected and thereby the added suffixes make them a tripartite syllabically matched set. It could be that for words and only for the words, the underlying length of the morpheme shows an effect where the features do not mismatch. But this is merely a conjecture and needs to be checked. Future studies may also better control all these parameters. It has to be mentioned, however, that due to constraints on the lexicon, triplets matching in all necessary aspects are difficult to find. Moreover, for the present study it was crucial to keep the word/pseudoword forms parallel and hence we opted for the stimuli as used here.

Note, that the present tests for Wordness effects cannot be compared to the previous experiments in this field (see Jacobsen et al., 2004; Pulvermüller and Shtyrov, 2006) where the difference in the lexical status was introduced between standards and deviants. Here we focused the experimental design on possible inferences of other levels of linguistic processing with the perception of phonological contrasts and the possible impact on the MMN.

In sum, the present study extends the neurobiological findings about the underspecification of the [CORONAL] place of articulation that has been demonstrated in isolated vowels (Eulitz and Lahiri, 2004) to more complex language processing situations, such as words and pseudowords. The present results also showed that phonological contrasts at the segmental level were primarily driving the MMN effects and not alternative factors of influence from higher levels of linguistic processing such as phonotactic probabilities or contextual influences. The reported pattern of MMN differences support the notion that mental representations of phonological place features for vowels are not a one-to-one relation between the acoustic speech signal and their mental representations. As the additional influence of other levels of linguistic processing was demonstrated, it seems favorable to use pseudowords for investigating phonological effects by means of MMN.

The reported MMN asymmetry between conditions strongly suggests that the brain refers to more abstract underspecified phonological representations in the mental lexicon during speech perception and that underspecification may be an important principle of the functional organization of the mental lexicon. Further research is, however, necessary to further generalize this notion, for instance from vowels to other speech sounds or to other phonological features.

4. Experimental procedures

4.1. *Participants*

A total of 24 students of the University of Konstanz participated in this electroencephalographic (EEG) study and were paid for their participation. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), native speakers of German with normal hearing and no history of neurological or psychiatric disorders. The data of 6 participants had to be excluded from all further analyses due to excessive electro-occulogram (EOG), cardiac or movement artifacts. The remaining 19 participants (age range 20–28; mean age 23 (SEM 0.63); and 9 females) with good raw-data quality were used for the final analysis. They were presented with standard and deviant stimuli in a passive oddball paradigm in eight experimental conditions.

4.2. *Stimuli*

The standard and deviant stimuli were three minimal pairs of German nouns (the German dative plural forms were used to get them paired; and subjects were instructed correspondingly) varying exclusively in their mid-vowels [e], [ø] and [o] of the first syllable ([meːrən] “oceans”, [møːrən] “carrots”, [moːrən] “swamps”) and three matched pseudowords ([meːkən], [møːkən], and [moːkən]) (Fig. 1). Due to constraints on the lexicon, triplets matching in all necessary aspects were difficult to find. Consequently, there were some lexical inflectional ambiguities. For instance [moːrən] has two possible lexical sources. On the one hand it can be the dative or accusative form *Mooren* of the word “swamp”, as well as the nominative plural form *Mohren* of the word “Moor”. Further, [møːrən] can be the nominative or dative plural of the same word *Möhren*, meaning “carrot”. Additionally [meːrən] can be the dative plural of *Meer* (“ocean”) or the infinitive of the verb form *mehren* (“to increase”). However it was crucial to keep the word/pseudoword forms parallel and hence we opted for more lexical complexity. However, the participants were instructed and biased towards the meaning of the dative plural of all three words. No ambiguity occurred for the pseudowords.

Syllables used to construct the stimuli were produced by a male speaker (30 years). The items were recorded multiple times and three variants per item were selected with comparable pitch and formant frequencies. The pseudowords were phonotactically legal and had no meaning in German. The stress was on the first syllable for all stimuli.

The acoustic structure of all stimuli was fairly similar, starting with a nasal [m] followed by varying mid-vowels [e], [ø], and [o], and a second syllable being [-ren] for the words, and [-ken] for the pseudowords.

For the present study, the critical differences were on the vowels of the first syllable which differed acoustically mainly in F2 and F3 formant frequencies (Fig. 2). The coronal vowel pair [ø] and [e] had larger F2 values than [o], whereas [o] and [ø] had smaller F3 values than [e], resulting in relatively close overall acoustic differences between all stimuli, with similar distances between [ø]–[e] and [ø]–[o]. Thus the feature distinctions were asymmetric, but the acoustic differences were symmetric. The F0 was close to each other for all vowels (97–101 Hz), the F1 was close to each other within each vowel category ([e] 287–314 Hz; [ø] 305–336 Hz; and [o] 496–535 Hz).

The surface word frequencies of [meːrən, møːrən, and moːrən] were similar (Table 2, fourth column) according to the Leipziger Wortschatz (http://wortschatz.uni-leipzig.de/) determined by log-values of the word form frequency counts.

Distributional frequencies of the speech sounds (phonotactic probabilities), meaning the sequential arrangement of phonemes in the syllables and words were controlled for the first critical consonant–vowel (C[V]) and consonant–vowel–consonant (C[V]C) syllables (Table 2). It has been shown (Bonte et al., 2005) that the distributional probabilities of phoneme clusters influence the processing of speech as well as the amplitude characteristics of the MMN (Picton et al., 2000).

Table 2 – Frequency of occurrence of phonemes and sequences of phonemes (log-values) for all words in the present study.

Word stimuli	m[V]	m[V]r	m[V]:rən
[me:rən]	3.18	3.11	0.54
[mø:rən]	3.16	0.58	0.54
[mo:rən]	2.95	1.01	0.58

Frequency counts were based on lemma form frequency in the CELEX corpus. [V] = critical vowel; [m] = sound as initial consonant for words and pseudowords; [r] = sound following all words. Note, that the frequency counts for m[V] are the same for words and pseudowords. The word frequencies (m[V]:rən) are based on the "Leipziger Wortschatz" (http://wortschatz.uni-leipzig.de/) as Celex does not include plural forms consistently. The word frequency of the infinitive verb form *mehren* ("to increase") — a homophone of [me:rən] was 0.48, the frequency of the nominative plural form *Mohren* ("moor") — a homophone of [mo:rən] was 0.50, thus comparable to the rest of the word frequencies.

These probabilities were determined by log-values of the frequency counts of phoneme sequences weighed for lemma frequency of the German Celex database (Baayen et al., 1995). The C[V] sequence were all similar to each other ([me] log-value 3.11; [mø] log-value 3.16; [mo] log-value 2.95), the C[V]C sequences showed the highest probability for [me:r] (log-value 3.11), following [mo:r] (log-value 1.01) and [mø:r] (log-value 0.58). Note, the word frequencies could not be determined by the Celex database as no plural forms are shown consistently which is why the Leipziger Wortschatz database was used.

To avoid differential effects of early acoustic cues, the critical syllables [mø:], [mo:] and [me:] were all cut to the same length (250 ms). In order to achieve complete acoustic similarity in the standard-deviant contrasts across stimulus pairs, we then cross-spliced the first syllables with the second syllables [-ren] and [-ken]. For example, the original [-ren] from [mø: -rən] was attached to a different [mø:-] originating from either [mø: -kən] or a different [mø: -rən]. This technique allowed us to circumvent a primarily acoustic explanation for differences between the vowel contrasts in the word and pseudoword blocks, since the MMN is highly sensitive to even minor acoustic differences between the standard and deviant stimuli. All stimuli were normalized to have the same peak sound energy. For the analysis and processing of the stimuli we used the PRAAT software (Boersma and Weenink, 2007).

To ensure exactly the same phonological context for each word such that there was a parallel pseudoword, we had to compromise on the inflectional ambiguities of the words. However, the subjects were instructed that they would hear inflected words.

The stimuli (words and pseudowords) of 588 ms duration were presented every 1088 ms with a fixed inter-stimulus interval (ISI) of 500 ms binaurally via headphones. By using six different variants of the same stimuli and presenting them randomly, acoustic variability was introduced to simulate more natural speech perception and thus forcing the processing system to map the incoming acoustic signals onto more abstract representations (Eulitz and Lahiri, 2004; Jacobsen et al., 2004; Phillips et al., 2000).

4.3. *Experimental procedure*

Each participant was presented with a passive oddball paradigm while their EEG was recorded. During the study, 510 (85%) standards and 90 (15%) deviants per word and pseudoword category and block were presented. A pseudo-random stimulus sequence was created so that there were at least 5 ± 2 standard stimuli between any two deviants. In each experimental session the three mid-vowel categories were combined in all possible pairs of words, except the [e]–[o] contrast, which we had to compromise for, to ensure an acceptable duration of the experiment. Each word and pseudoword served as a standard and as deviant, resulting in eight blocks, four word blocks and four pseudoword blocks (Table 3). The order of blocks was counterbalanced across subjects.

4.4. *Data acquisition and analysis*

Participants were seated comfortably in an electrically and sound-attenuated chamber and watched a silent movie of their choice during the experiment. They were instructed to ignore the word/pseudoword stimuli presented via headphones while their electroencephalogram (EEG) was continuously recorded (TMS International, Type Porti-S/64) from 64 electrode positions (Easycap, Montage M10 to 10% System). All electrodes were average-referenced during the EEG measurements. The AC signals were recorded and sampled at 512 Hz. Interelectrode impedances were kept below 5 kΩ. Vertical and horizontal eye movements (EOGs) were co-registered bipolar with an additional electrode located on the forehead in order to correct the EEG raw data for eye movements using the algorithm implemented in the Brain Electric Source Analysis software (BESA; MEGIS Software GmbH). During the study participants were asked to sit quietly and avoid excessive eye movements. Further off-line data processing included a digital band-pass filter set to 1–30 Hz and a standardization from 64 channels to 81 channels. Event-related potentials (ERPs) were gained by averaging epochs, which started 200 ms before the word/pseudoword onset and ended 700 ms thereafter; the time interval from −200 to 0 was used as baseline. Epochs with voltage variation exceeding 80 μV at any EEG channel (after

Table 3 – German words and pseudowords used in the 8 experimental conditions.

Conditions		Standard	Deviant
Words	$[ø]_{/o/}$	[mo:rən]	[mø:rən]
	$[o]_{/ø/}$	[mø:rən]	[mo:rən]
	$[ø]_{/e}$	[me:rən]	[mø:rən]
	$[e]_{/ø/}$	[mø:rən]	[me:rən]
Pseudowords	$[ø]_{/o/}$	[mo:kən]	[mø:kən]
	$[o]_{/ø/}$	[mø:kən]	[mo:kən]
	$[ø]_{/e}$	[me:kən]	[mø:kən]
	$[e]_{/ø/}$	[mø:kən]	[me:kən]

All stimuli were matched for their acoustic properties. The standard-deviant contrasts are identical within the reversal of vowel contrasts for words and pseudowords. The underlying gray areas highlight the only conflicting condition $[ø]_{/o/}$.

EOG correction) were rejected. For each participant, the averaged MMN responses contained at least 95% accepted deviant trials in each condition. All responses were re-referenced offline against right and left mastoids for further analysis of the MMN effects.

Following Eulitz and Lahiri (2004) the MMN as difference waveform was obtained by subtracting the response to the standard from that to the deviant stimulus. The so called same-stimulus differences were calculated by using the recordings of two corresponding blocks. For instance, the standard [mø:rən] of the block with [mo:rən] as deviant was subtracted from the [mø:rən]-deviant of the reversed block with [mo:rən] as standard. This method provides a reliable measure to avoid confounds by variation in ERP morphology that may result from stimulus differences per se.

For statistical analysis, the MMN mean amplitude (40 ms time windows) around the peak latency of the grand average waveform for each condition was used as the dependent variable (Schröger, 1998). The mean amplitude was measured at the Fz electrode (re-referenced against linked mastoids) taken from the expected MMN latency window between 100 and 250 ms after change onset (vowel onset), thus in a window between 200 and 350 ms for each individual difference wave.

A three-way repeated-measures ANOVA for each mean amplitude value with the factors Wordness (word vs. pseudoword), Pair of Inversion showing an equalized acoustic change (non-conflicting pair $[e]_{/ø/}$ vs. $[ø]_{/e/}$ vs. conflicting pair $[ø]_{/o/}$ vs. $[o]_{/ø/}$) and Direction of Acoustic Change of the F2 formant frequency between the deviant and standard (F2 falling: $[ø]_{/e/}$ vs. $[o]_{/ø/}$ vs. F2 rising: $[e]_{/ø/}$ vs. $[ø]_{/o/}$) was performed. Only significant main effects or interactions are reported. For post-hoc tests in case of significant interactions paired *F*-tests were used. The Greenhouse–Geisser adjustment was used wherever appropriate. The presence of MMN was ensured using two-tailed *t*-tests for dependent variables separately for each condition.

Acknowledgments

Research was supported by a grant of the Schwerpunktprogramm 1234 (SPP1234) of the German Research Foundation (DFG) awarded to CE and AL using equipment provided by the University of Konstanz and the DFG. We would also like to thank for the technical and further support given by A. Bobrov, G. Salagan and A. Wetterlin.

REFERENCES

Baayen, R., Piepenbrock, R., Gulikers, L., 1995. The CELEX Lexical Database (Release 2) [cd-rom]. Linguistic Data Consortium, University of Pennsylvania, Philadelphia, PA. [Distributor].

Bishop, D.V.M., O'Reilly, J.O., McArthur, G.M., 2005. Electrophysiological evidence implicates automatic low-level feature detectors in perceptual asymmetry. Cogn. Brain Res. 24, 177–179.

Boersma, P., Weenink, D., 2007. PRAAT: Doing Phonetics by Computer (Ver. 4.6.38). Institut for Phonetic Sciences, Amsterdam.

Bonte, M.L., Mitterer, H., Zellagui, N., Poelmans, H., Blomert, L., 2005. Auditory cortical tuning to statistical regularities in phonology. Clin. Neurophysiol. 116, 2765–2774.

Bybee, J., 2001. Phonology and Language Use. Cambridge University Press, Cambridge, UK, pp. 1–260.

Connine, C.M., Pinnow, E., 2006. Phonological variation in spoken word recognition: episodes and abstractions. Linguist. Rev. 23, 235–245.

Connine, C.M., Blasko, D., Titone, D., 1993. Do the beginnings of spoken words have a special status in auditory word recognition. J. Mem. Lang. 32, 193–210.

Connine, C.M., Titone, D., Deelman, T., Blasko, D., 1997. Similarity mapping in spoken word recognition: evidence from phoneme monitoring. J. Mem. Lang. 37, 463–480.

Cowan, N., Winkler, I., Teder, W., Näätänen, R., 1993. Memory prerequisites of mismatch negativity in the auditory event-related potential (ERP). J. Exp. Psychol. Learn. Mem. Cogn. 19, 909–921.

Dehaene-Lambertz, G., 1997. Electrophysiological correlates of categorical phoneme perception in adults. Neuroreport 8, 919–924.

Endrass, T., Mohr, B., Pulvermüller, F., 2004. Enhanced mismatch negativity brain response after binaural word presentation. Eur. J. Neurosci. 19, 1653–1660.

Eulitz, C., Lahiri, A., 2004. Neurobiological evidence for abstract phonologica representations in the mental lexicon during speech recognition. J. Cogn. Neurosci. 16, 577–583.

Fitzpatrick, J., Wheeldon, L.R., 2000. Phonology and phonetics in psycholinguistic models of speech perception. In: Burton-Roberts, N., Carr, P., Docherty, G. (Eds.), Phonological Knowledge: Conceptual and Empirical Issues. Oxford University Press, Oxford, pp. 131–160.

Friedrich, C.K., Eulitz, C., Lahiri, A., 2006. Not every pseudoword disrupts word recognition: an ERP study. Behav. Brain Funct. 2, 36.

Friedrich, C.K., Lahiri, A., Eulitz, C., 2008. Neurophysiological evidence for underspecified lexical representations: asymmetries with word initial variations. J. Exp. Psychol. Hum. Percept. Perform. 34, 1545–1559.

Gaskell, M., 2003. Modelling regressive and progressive effects of assimilation in speech perception. J. Phon. 31, 447–463.

Gaskell, M.G., Marslen-Wilson, W.D., 1996. Phonological variation and inference in lexical access. J. Exp. Psychol. Hum. Percept. Perform. 22, 144–158.

Gaskell, M.G., Marslen-Wilson, W.D., 1998. Mechanisms of phonological inference in speech perception. J. Exp. Psychol. Hum. Percept. Perform. 24, 380–396.

Gaskell, M., Snoeren, N., 2008. The impact of strong assimilation on the perception of connected speech. J. Exp. Psychol. Hum. Percept. Perform. 34, 1632–1647.

Gow Jr., D.W., 2002. Does English coronal place assimilation create lexical ambiguity? J. Exp. Psychol. Hum. Percept. Perform. 28, 163–179.

Gumnior, H., Zwitserlood, P., Bölte, J., 2005. Assimilation in existing and novel German compounds. Lang. Cogn. Processes 20, 465–488.

Jacobsen, T., 2004. Mismatch negativity to frequency changes: no evidence from human event-related brain potentials for categorical speech processing of complex tones resembling vowel formant structure. Neurosci. Lett. 362, 204–208.

Jacobsen, T., Horváth, J., Schröger, E., Lattner, S., Widmann, A., Winkler, I., 2004. Pre-attentive auditory processing of lexicality. Brain Lang. 88, 54–67.

Johnson, K., 1997. Speech perception without speaker normalization: an exemplar model. In: Johnson, K., Mullenix, J.W. (Eds.), Talker Variability in Speech Processing. Academic Press, San Diego, pp. 145–166.

Klatt, D.H., 1989. Review of selected models of speech perception. In: Marslen-Wilson, W. (Ed.), Lexical Representation and Process. MIT Press, Cambridge, MA, pp. 169–226.

Lahiri, A., Marslen-Wilson, W., 1991. The mental representation of lexical form: a phonological approach to the recognition lexicon. Cognition 38, 245–294.
Lahiri, A., Reetz, H., 2002. Underspecified recognition. In: Gussenhoven, C., Warner, N. (Eds.), Laboratory Phonology VII K. Mouton de Gruyter, Berlin, pp. 637–677.
Lahiri, A., Reetz, H., 2010. Distinctive features: phonological underspecification in representation and processing. J. Phon. 38, 44–59.
Marslen-Wilson, W., Nix, A., Gaskell, G., 1995. Phonological variation in lexical access: abstractness, inference and English place assimilation. Lang. Cogn. Processes 10, 285–308.
McQueen, J., 2005. Speech perception. In: Lamberts, K., Goldstone, R. (Eds.), The Handbook of Cognition. SAGE Publications Ltd., London–Thousand Oaks–New Delhi, pp. 255–275.
Mitterer, H., 2003. Understanding Gardem bench: studies on the perception of assimilated word forms [Dissertation], Universiteit Maastricht, Maastricht, The Netherlands.
Mitterer, H., Blomert, L., 2003. Coping with phonological assimilation in speech perception: evidence for early compensation. Percept. Psychophys. 65, 956–969.
Näätänen, R., 1992. Attention and Brain Function. Erlbaum, Hillsdale.
Näätänen, R., 2001. The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). Psychophysiology 38, 1–21.
Näätänen, R., Winkler, I., 1999. The concept of auditory stimulus representation in cognitive neuroscience. Psychol. Bull. 125, 826–859.
Näätänen, R., Gaillard, A., Mäntysalo, S., 1978. Early selective-attention effect on evoked potential reinterpreted. Acta Psychol. 42, 313–329.
Näätänen, R., Schröger, E., Karakas, S., Tervaniemi, M., Paavilainen, P., 1993. Development of a memory trace for a complex sound in the human brain. Neuroreport (Oxford) 4, 503–506.
Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., Vainio, M., Alku, P., Ilmoniemi, R.J., Luuk, A., Allik, J., Sinkkonen, J., Alho, K., 1997. Language-specific phoneme representations revealed by electric and magnetic brain responses. Nature 385, 432–434.
Näätänen, R., Paavilainen, P., Rinne, T., Alho, K., 2007. The mismatch negativity (MMN) in basic research of central auditory processing: a review. Clin. Neurophysiol. 118, 2544–2590.
Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh Inventory. Neuropsychologia 9, 97–113.
Pettigrew, C.M., Murdoch, B.E., Ponton, C.W., Finnigan, S., Alku, P., Kei, J., Sockalingam, R., Chenery, H.J., 2004. Automatic auditory processing of English words as indexed by the mismatch negativity, using a multiple deviant paradigm. Ear Hear. 25, 284–301.
Phillips, C., Pellathy, T., Marantz, A., Yellin, E., Wexler, K., Poeppel, D., McGinnis, M., Roberts, T., 2000. Auditory cortex accesses phonological categories: an MEG mismatch study. J. Cogn. Neurosci. 12, 1038–1055.
Picton, T.W., Alain, C., Otten, L., Ritter, W., Achim, A., 2000. Mismatch negativity: different water in the same river. Audiol. Neurootol. 5, 111–139.
Poeppel, D., Idsardi, W.J., van Wassenhove, V., 2008. Speech perception at the interface of neurobiology and linguistics. Philos. Trans. R. Soc. Lond. B Biol. Sci. 363, 1071–1086.
Pulvermüller, F., Shtyrov, Y., 2006. Language outside the focus of attention: the mismatch negativity as a tool for studying higher cognitive processes. Prog. Neurobiol. 79, 49–71.
Pulvermüller, F., Kujala, T., Shtyrov, Y., Simola, J., Tiitinen, H., Alku, P., Alho, K., Martinkauppi, S., Ilmoniemi, R.J., Näätänen, R., 2001. Memory traces for words as revealed by the mismatch negativity. Neuroimage 14, 607–616.
Pulvermüller, F., Shtyrov, Y., Kujala, T., Näätänen, R., 2004. Word-specific cortical activity as revealed by the mismatch negativity. Psychophysiology 41, 106–112.
Schröger, E., 1996. A neural mechanism for involuntary attention shifts to changes in auditory stimulation. J. Cogn. Neurosci. 8, 527–539.
Schröger, E., 1998. Measurement and interpretation of the mismatch negativity. Behav. Res. Methods Instrum. Comput. 30, 131–145.
Shtyrov, Y., Pulvermüller, F., 2002. Neurophysiological evidence of memory traces for words in the human brain. NeuroReport 13, 521–526.
Shtyrov, Y., Pulvermüller, F., 2007. Language in the mismatch negativity design: motivations, benefits, and prospects. J. Psychophysiol. 21, 176–187.
Shtyrov, Y., Kujala, T., Palva, S., Ilmoniemi, R.J., Näätänen, R., 2000. Discrimination of speech and of complex nonspeech sounds of different temporal structure in the left and right cerebral hemispheres. Neuroimage 12, 657–663.
Shtyrov, Y., Osswald, K., Pulvermüller, F., 2008. Memory traces for spoken words in the brain as revealed by the hemodynamic correlate of the mismatch negativity. Cereb. Cortex 18, 29–37.
Stevens, K., 2002. Toward a model for lexical access based on acoustic landmarks and distinctive features. J. Acoust. Soc. Am. 111, 1872–1891.
Stevens, K., Keyser, S., 2010. Quantal theory, enhancement and overlap. J. Phon. 38, 10–19.
Tavabi, K., Elling, L., Dobel, C., Pantev, C., Zwitserlood, P., 2009. Effects of place of articulation changes on auditory neural activity: a magnetoencephalography study. PLoS One 4, e4452. doi:10.1371/journal.pone.0004452.
Walter, M., Hacquard, V., 2004. 'MEG evidence for phonological underspecification'. MIT Phonology Circle.
Wheeldon, L., Waksler, R., 2004. Phonological underspecification and mapping mechanisms in the speech recognition lexicon. Brain Lang. 90, 401–412.
Winkler, I., 2007. Interpreting the mismatch negativity. Psychophysiology 21, 147–163.
Winkler, I., Cowan, N., Csépe, V., Czigler, I., Näätänen, R., 1996. Interactions between transient and long-term auditory memory as reflected by the mismatch negativity. J. Cogn. Neurosci. 8, 403–415.
Yasin, I., 2007. Hemispheric differences in processing dichotic meaningful and non-meaningful words. Neuropsychologia 45, 2718–2729.
Zimmerer, F., Reetz, H., Lahiri, A., 2009. Place assimilation across words in running speech: corpus analysis and perception. J. Acoust. Soc. Am. 125, 2307–2322.