Brain electric activity reflects the underspecification of phonological features in the mental lexicon

Carsten Eulitz[†‡], Aditi Lahiri[‡], Jonas Obleser[†] and Henning Reetz[‡]

† Department of Psychology, University of Konstanz, Germany

‡ Department of Linguistics, University of Konstanz, Germany

E-mail: {carsten.eulitz,aditi.lahiri,jonas.obleser,henning.reetz}@uni-konstanz.de

ABSTRACT

No word is ever pronounced alike twice and the brain has limited capacities to store and manage information. Under these constraints, abstract underspecified representations where not all phonemic features are stored in the mental lexicon seem to be an effective way to store contrastive information. This proposal, as spelled out in the FUL-model, was examined using event-related brain potentials, i.e. the mismatch negativity (MMN), an automatic change detection response in the brain which is sensitive to language-specific phoneme representations. Subjects were listening to the natural German vowels [o], [ø] and [e]. Across different blocks, vowel pairs were presented to subjects, reversed as standard and deviant. Models not assuming underspecification predict equal MMNs for vowel pairs regardless of the reversal. In contrast, enhanced and earlier MMNs were observed for those conditions where the standard is phonologically underspecified in the mental representation. This result provides first neurobiological evidence for a featurally underspecified mental lexicon.

1. INTRODUCTION

A central issue connecting the study of speech perception and brain research is the nature of the mental representation involved in the processing of speech sounds of natural languages. Two fundamentally different views on the mental representation of phonemes have been entertained in the literature. One view assumes that the phonemes correspond directly to their acoustic signal properties or to some surface representation (SR-models) closely akin to the signal [1], [2]. Exemplar models of Miller [3] and Bybee [4] would also fall under SR-models, since they assume that the stored mental representation contains a great deal phonetic detail and all word variants. Under the opposing view, mental representations are more abstract and not isomorphic with the surface form. Such underlying mental representations comprise of a small number of discrete phonological features, with variable surface forms of words derived from single representations. We adopt an even more stringent feature-based approach (Featurally Underspecified Lexicon - FUL) which maintains that the features derived from the acoustic signal are mapped onto a mental representation which is phonologically underspecified. The features that are not specified in the underlying representation are not just redundant features, but also features that are contrastive but non-active in the phonology of specific languages [5], [6] (see also [7] for a review). Evidence for underspecified representations such as described in the FUL-model have been deduced from language comprehension experiments as well as from language change. The FUL-model assumes that place of articulation features like [CORONAL] are not usually specified unless the language happens to have a two-way coronal contrast. Such a hypothesis leads to the assumption that /n/ would be underspecified for place while /m/ would be specified as [LABIAL], and the former would be vulnerable to regressive assimilation rules. The underspecification accounts for coronal-assimilations like '*ten bells*' possibly becoming '*tem bells*', but words like 'trim' would remain invariant with no possibility of '*trim girls*' becoming '*tring girls*'. SR-models on the other hand would incorporate all variations of 'ten' in the mental representation and would have to independently specify that a dental/alveolar consonant is likely to have more surface variants than a labial one.

An essential ingredient of the speech perception mechanism of the FUL-model is the mapping process which goes hand in hand with the underspecified representations. The FUL-model assumes that a number of features from the signal *conflict* with certain features in the representation. For instance, [HIGH] from the signal (for example from [i]) would conflict with [LOW] of /a/ in the underlying representation. Mid vowels are, however, not specified for height and the [HIGH] from [i] would not conflict with the representation of /e/. That is a phonetic [i] would be accepted as a variant of /e/ but not of /a/. Similarly, [CORONAL] from a surface [d] would conflict with an underlying [LABIAL] of /b/. But the opposite, viz. feature [LABIAL] from phonetic surface [b] would be a *non-conflict* for underlying /d/ since its place of articulation [CORONAL] is not specified.

We used the Mismatch Negativity (MMN) to explore underspecified representations in the mental lexicon. The MMN, an automatic change detection response in the brain, has been shown to be an index of experience-dependent memory traces which are sensitive to language-specific phoneme representations [8], [9]. The MMN can be measured in oddball paradigms and is elicited by infrequent, deviant stimuli presented after a random number of frequent, standard stimuli. The standard stimuli

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create a central sound representation which is more abstract than the sum of perceived acoustic elements and can also be shaped by long term memory information [9]. Consequently, the central sound representation may correspond to the underlying representation of phonemes. The infrequent, deviant stimulus contains information more directly related to the sound perception and might therefore correspond to the set of surface phonological features, i.e. the surface form. Therefore, the MMN can be an instrument to study the degree of correspondence between the surface form, extracted from the deviant, and the underlying representation, created by the standard.

Predictions of the FUL-model were tested by comparing symmetric and asymmetric sets of phonological features in standard and deviant stimuli using natural German vowels [o], [ø] and [e]. As summarised in table 1, the FUL-model assumes that the features of these vowels are not all specified in the mental representation.

Table I. Phonological features in the surface and the underlying representation (according to the FUL-model) of the vowels used in the present study

	e	ø	o
Features in the underlying representation	[---]	[---] [LABIAL]	[DORSAL] [LABIAL]
Features from the signal	[CORONAL]	[CORONAL] [LABIAL]	[DORSAL] [LABIAL]

The FUL-model further assumes that the feature [CORONAL] from the signal is incongruent with [DORSAL] and conflicts with it in the lexical representation. That is, the [CORONAL] feature extracted from the surface [e] and [ø] would conflict with the underlying representation of [DORSAL] of /o/. However, the [DORSAL] feature extracted from the surface [o] would be a non-conflict with /e/ and /ø/ since the place of articulation [CORONAL] is not specified and hence not available for a conflict. So the crucial comparisons for our purposes are the acoustically equidistant stimuli [o] vs. [ø] and [ø] vs.[e].

2. MATERIALS AND METHODS

The standard and deviant stimuli were three different tokens of the three German vowels [e] (as in *bay*), [ø] (as in *Goethe*) and [o] (as in *go*), spoken by a male speaker. Acoustically, the vowels differed in F2 and F3, the tongue height, corresponding to F1, having been kept almost constant. Stimuli of 200 ms duration (50 ms onset and offset ramps) were presented every 700 ms with a fixed intertrial interval binaurally via headphones. By using three tokens of each vowel, acoustic variability was introduced to simulate more natural speech perception conditions and thereby force the processing system to map the incoming acoustic signals onto more abstract representations. Twelve right handed undergraduate students of psychology (50% female; aged 21-30 years) underwent an electroencephalographic (EEG) study where two vowel categories were presented as standard and deviant stimuli in a passive oddball paradigm. In each experimental session the three vowel categories were combined in all possible pairs, with each vowel serving as a standard as well as a deviant, resulting in six blocks. The order of blocks was counterbalanced across subjects. During the recordings subjects read a self chosen book.

The MMN was extracted from the difference waveforms (deviant - standard). An example for standard-, deviant-, as well as the corresponding difference waveforms evoked by vowels are shown in Fig.1. In the present study, we calculated the within-vowel-category-differences: For instance, the MMN-waveform to [e]-deviant measured in a block where /ø/ was the standard was calculated as [e]-deviant minus /e/-standard and will be reported as $[e]_{/ø/}$.

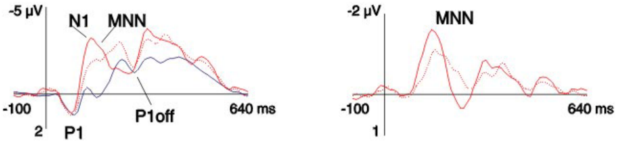

Fig.1 The left column shows an example for vowel-evoked standard (blue line) and two different deviant (red lines) waveforms. The corresponding difference waveforms are presented in the right column. Note the different scaling of the y-axis. The most relevant components of the event-related brain responses are marked.

From the difference waveforms we derived the dependent variables. These were (i) the MMN-latency measured at the maximum amplitude of the MMN at the Fz-electrode position in the latency range from 90-210 ms post stimulus onset, and (ii) the MMN-amplitude at Fz position measured as the mean amplitude across 80 ms centered at the mean MMN-latency across subjects in the corresponding experimental condition.

3. RESULTS AND DISCUSSION

The crucial comparisons for our purposes are the acoustically equidistant stimuli [o] vs. [ø] and [ø] vs.[e]. Comparing the MMN of these stimuli revealed different amplitudes and MMN latencies <u>only</u> when the phonological feature sets in the standard and deviant stimuli were asymmetric (e.g. $[ø]_{/o/}$ vs. $[o]_{/ø/}$) and not when they showed a similar acoustic contrast but were symmetric (e.g. $[ø]_{/e/}$ vs. $[e]_{/ø/}$). Fig. 2 demonstrates these effects for the latency and the amplitude of the MMN. These were shown to be statistically significant using a two-way repeated measures ANOVA with the factors pair of inversion (with equal acoustic change, i.e. $[ø]_{/e/}$ vs. $[e]_{/ø/}$ and $[ø]_{/o/}$ vs. $[o]_{/ø/}$) and direction of change of the F2-frequency between deviant and standard (upwards for $[e]_{/ø/}$ and $[ø]_{/o/}$ vs. downwards for $[ø]_{/e/}$ and $[o]_{/ø/}$). The prediction of the FUL-model would be an interaction of the factors whereas all varieties of SR-models would predict no interaction but just main effects. The MMN latency ($F(1/11)=10.53$; $p<0.01$) as well as the MMN amplitude at the frontal electrode position Fz

(F(1/11)=5.21; p<0.05) showed statistically significant interactions as predicted by the FUL-model.

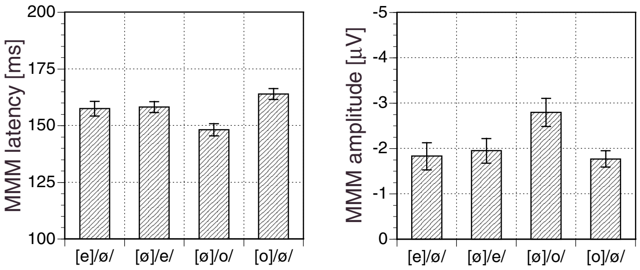

Fig. 2 Mean peak latencies ± s.e.m. (left side) and amplitudes ± s.e.m. (right side) of the MMN for the critical experimental conditions (see text). Note the larger amplitude and the shorter latency of the MMN only in the [ø]$_{/o/}$ condition, i.e. when the phonological feature sets in the standard and deviant stimuli showing a *conflict* but not when showing a *non-conflict* according to the FUL-model.

This is evidence that in addition to mere acoustic changes, what influences the MMN is the conflict between the features of the actually encoded vowel (deviant) with those specified in the mental representation (created by the standard stimulus). The same acoustic contrasts trigger differential MMNs when they are reversed as standard and deviant in conflict situations, but not when both conditions of the pair of inversion are non-conflicting. Thus, the asymmetry predicted by the phonologically underspecified mental representations is borne out by the neurobiological evidence. We conclude that rather abstract underspecified mental representation should be entertained to account for the way in which acoustic variation is handled by listeners.

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