Magnetic Mismatch Field Elicited by Phonological Feature Contrast

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Abstract

Although membership in some linguistic categories is a gradient property (e.g. semantic, phonetic categories), membership in the formal categories of phonology and syntax is an all-or-nothing property. A defining characteristic of discrete phonological categories (such as /p/, /t/, and /k/) is that phonological processes treat all members of the category as *exactly the same*. Therefore, the best evidence that a neural system recognizes categorial representations is evidence that all members of the category are treated as the same.

In these experiments we use the auditory mismatch paradigm -- normally a measure of discrimination -- as a measure of when acoustically different sounds are treated as the same. We show that an auditory mismatch response is elicited by a sequence of stimuli in which there is a many-to-one ratio at a higher-level phonological level, but no such distribution at an acoustic level, a finding which indicates access to discrete phonological representations.

Our experiments show that the auditory mismatch response is sensitive to representations in which groups of different phonological categories are treated as the same. Specifically, voiced consonants (/b/, /d/, /g/) are treated as a group, contrasting with the voiceless consonants (/p/, /t/, /k/). This indicates that a neural system in auditory cortex has access to categorial representation of the phonological feature [±voice].

Acknowledgments

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Introduction

Phonological Categories

Phonological categories are not primitives of phonological representation. Evidence from language learning, language change, language breakdown and cross-linguistic phonological analysis shows that phonological categories are organized into *natural classes* of phonemes. These natural classes are assumed to share subphonemic features, such as [+voice] or [–voice]. So, just as phoneme categories group together many different acoustic tokens, so phonological features group together sets of different phoneme categories.

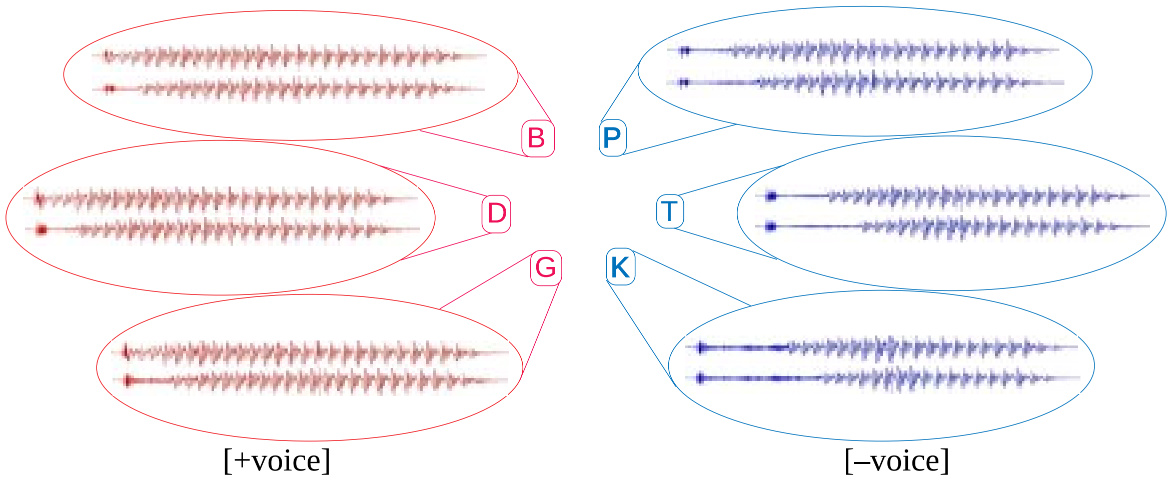
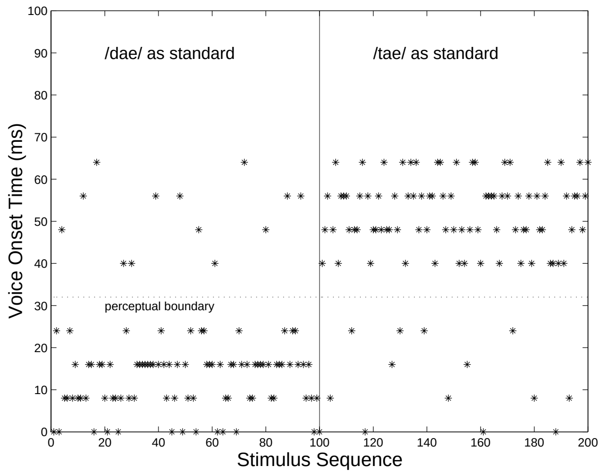


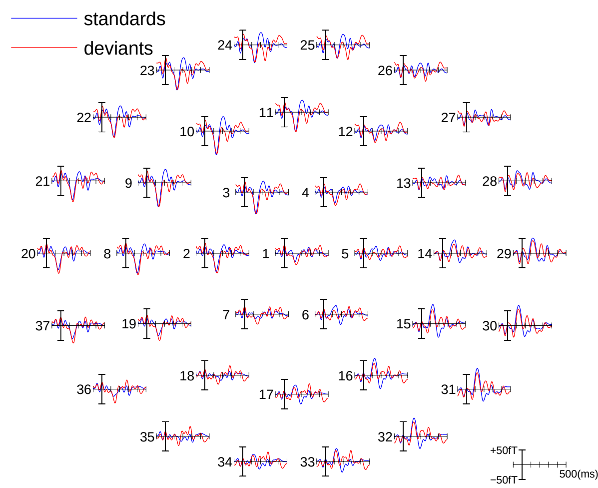
Figure 1: Phonological grouping of oral stop consonants according to [±voice]

Previous Studies

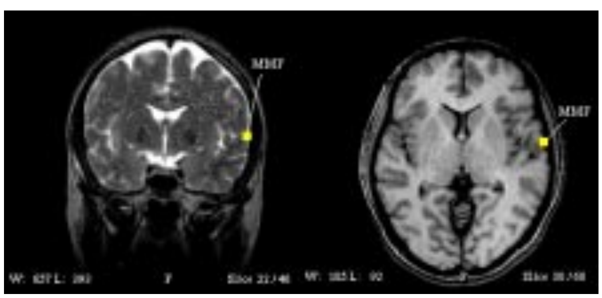
A number of studies have demonstrated that the auditory cortex mismatch response is sensitive to language-specific phonetic information, focusing on how knowledge of specific languages affects the gradient property of acoustic discrimination (Aaltonen et al. 1997, Dehaene-Lambertz 1997, Näätänen et al. 1997, Winkler et al. 1999). Previous work by our group has shown that the mismatch response is sensitive to the all-or-nothing property of phonological category membership. Phillips et al. (1999) show that a mismatch response is elicited by a sequence of /dæ/ and /tæ/ stimuli in which there is a many-to-one ratio at the phonological level, but not at the acoustic level. The observed mismatch response indicates that the generator of the mismatch response accesses discrete phonological categories. This is supported by a control experiment which preserved the acoustic distribution of stimuli, but removed the many-to-one ratio at the phonological level.



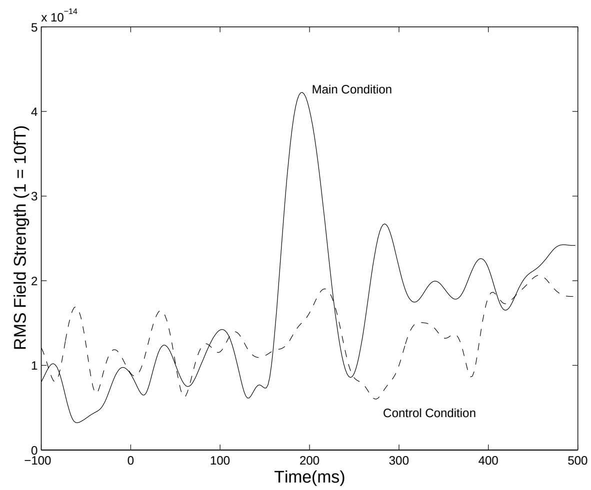
A: Schematic of experiment design: main condition; in control condition all VOT values are increased such that there is no many-to-one ratio at the phonological level.



B: Overlay of Grand Average Responses to standard and deviant /dæ/ stimuli.



C: MRI Overlay of single dipole model of /dæ/ MMF in one female subject.



D: RMS field strength of dipolar MMF in main and control conditions: computed based on adjusted difference wave in which mean MMF field strength across channels is zero at every time interval.

Figure 2: Design and results of earlier study of /dæ-tæ/ contrast (Phillips et al. 1999)

Method

Subjects

12 healthy normal adults (5 females) participated in all stages of the experiment. All subjects in the MEG experiment were strongly right-handed, as measured by the Edinburgh Handedness Inventory. All subjects gave informed consent for their participation.

Stimuli

All stimuli were synthesized CV syllables, generated with the Klatt synthesizer. Within each of three places of articulation (labial, alveolar, velar) stimuli varied in voice onset time (VOT). Place of articulation was distinguished by the onset frequencies of F2 and F3. The duration of the F1 transition was shorter for labial and longer for velar stimuli, as in natural speech.

Identification Pretest

All subjects in the MEG experiment first participated in a behavioral identification task in which 13 stimuli from each of the 3 VOT continua was classified as voiced or voiceless using a button-press response. This experiment confirmed that perceptual boundaries are shortest for labial stops and longest for velar stops, even when stimuli with different places of articulation are presented in the same sequence.

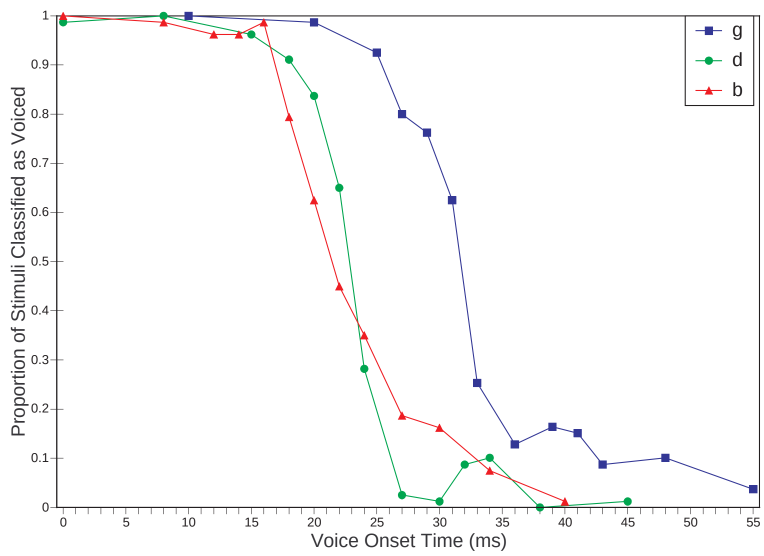


Figure 3: Identification judgments to stimuli from the three VOT continua

Isolating Phonological Contrasts

Based on the pretest, 4 different tokens of each of the 6 phonological categories were selected for each subject (i.e. 12 voiced, 12 voiceless) for the MEG experiment. In the main condition, stimuli were chosen randomly from one voicing category on 88% of the trials, and randomly from the other voicing category on 12% of trials. Due to the substantial acoustic variation within each voicing category, there was no many-to-one ratio at the acoustic level. In the second half of the experiment the standard and deviant categories were reversed.

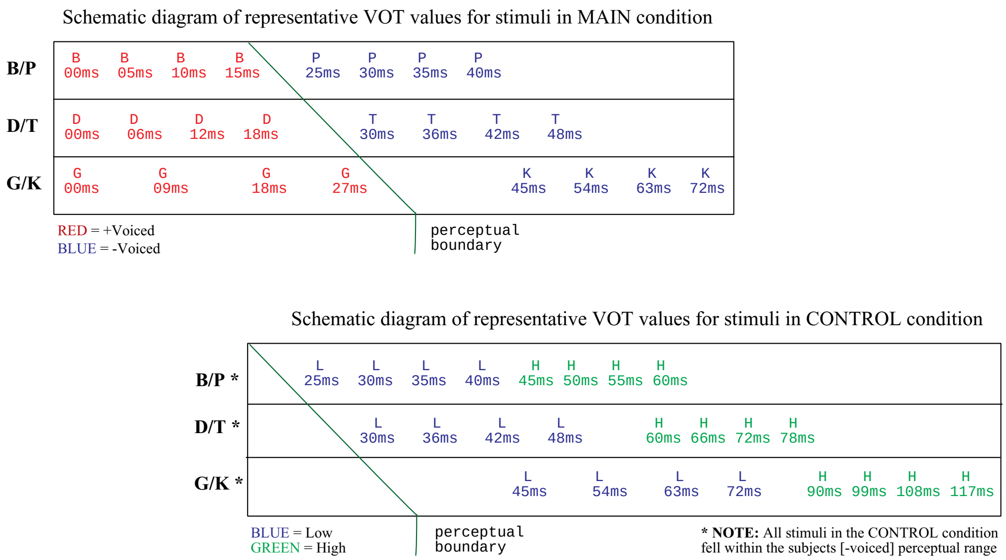


Figure 4: Typical Set of Stimuli for Main and Control Conditions

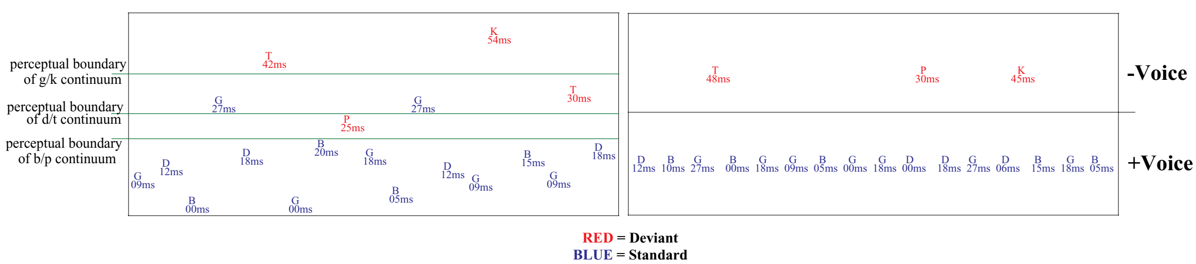


Figure 5: Acoustic versus Phonological Distribution of Stimuli in one half of Main Condition (standards and deviants are reversed in other half).

In the control condition, the acoustic variability among stimuli was preserved, but all stimuli were phonologically voiceless, so that there was no longer a many-to-one ratio at the phonological level.

MEG Recordings

MEG recordings were made using a 64-channel whole-head array of first order axial gradiometers at the KIT/MIT MEG-laboratory. Subjects lay on their back inside a magnetically shielded room. Most recordings were made between 2am and 5am in order to avoid artifacts due to the nearby subway line. Subjects listened passively to the stimulus sequence, which lasted around 30 minutes for each condition. Recordings were selectively averaged off line and filtered using a 0.5 Hz to 40 Hz bandpass filter.

Subjects were excluded from further analysis if they failed to show a clearly defined auditory M100 response in a pretest consisting of a sequence of 100 1 kHz tones. 4 subjects were excluded for this reason (mostly because the brain responses were masked by daytime environmental noise).

Results

Main Condition

At sensors which show clear auditory M100 responses, grand average responses to standard and deviant stimuli are very similar up to a latency of 100-150ms, but diverge in the 150-250 ms time window characteristic of MMF responses. The difference-related field exhibits a polarity inversion from anterior to posterior sensors. The dipolar MMF was confirmed by a repeated-measures ANOVA on a set of 5 anterior and 5 posterior channels (stimulus-type x channel-group interaction: $F(1,7) = 16.54$, $p < 0.0001$). No significant dipolar MMF was observed in the right hemisphere ($F(1,7) = 0.03$, $p = 0.85$).

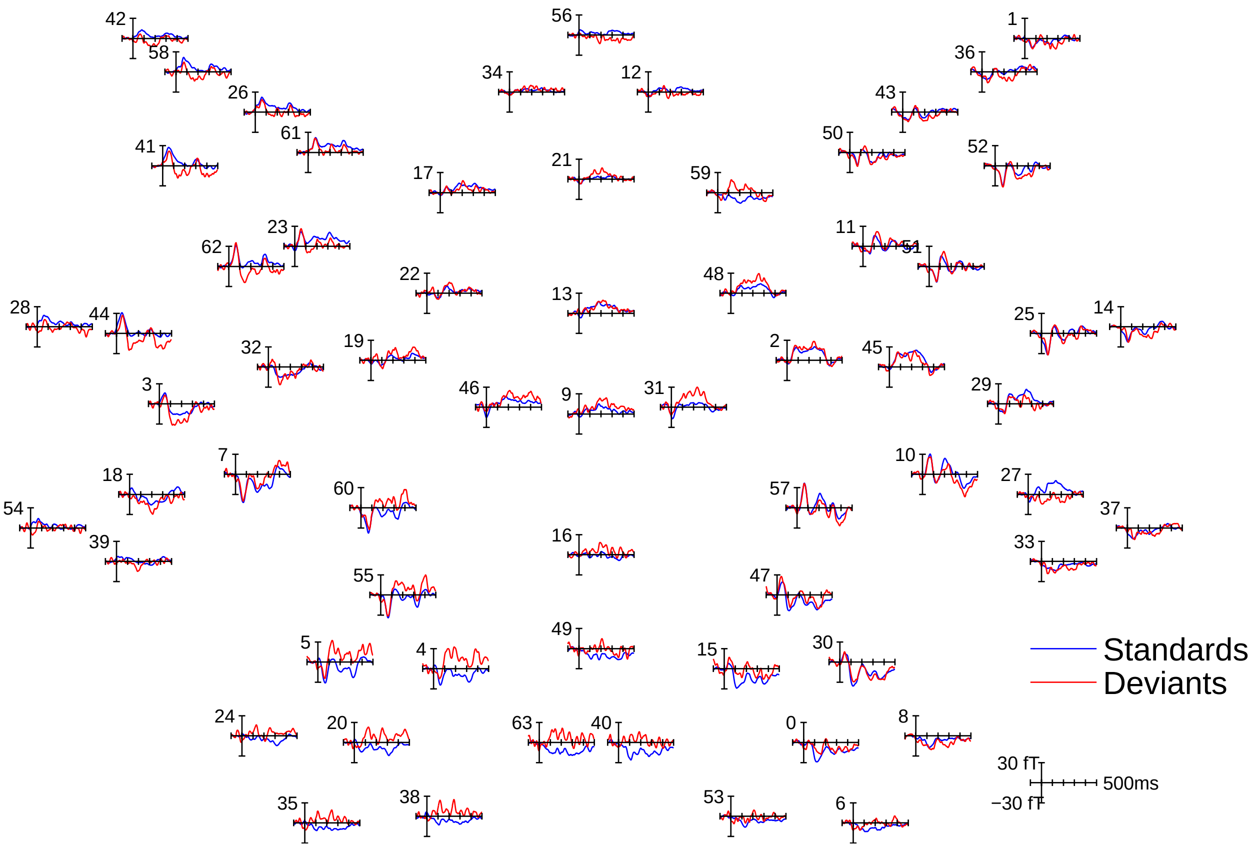
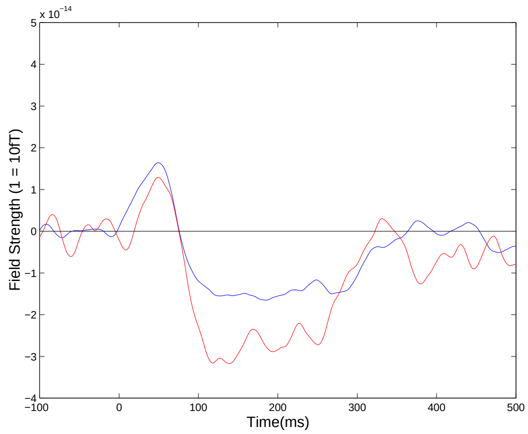
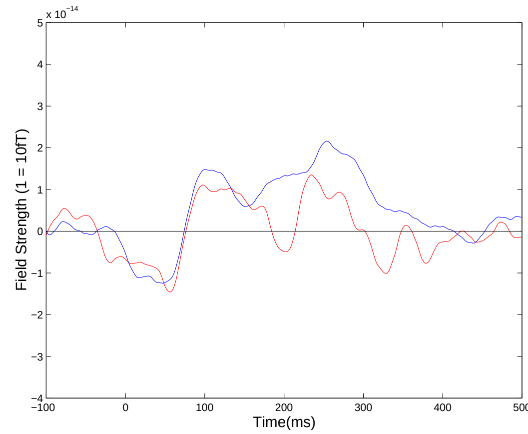


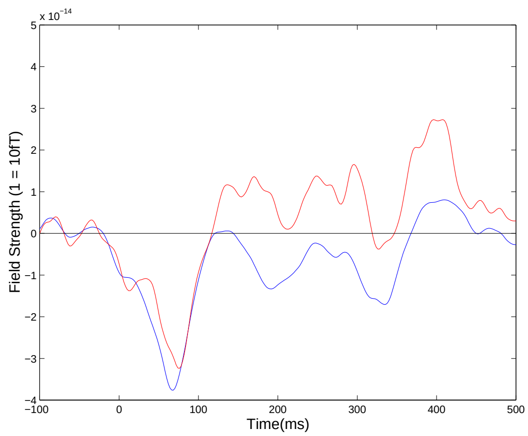
Figure 6: Grand average responses to standard (blue) and deviant (red) stimuli in main condition



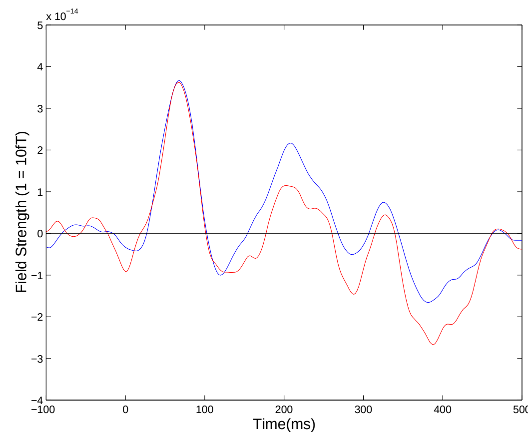
Individual Left Anterior Channel (#3)



Individual Right Anterior Channel (#29)



Individual Left Posterior Channel (#60)



Individual Right Posterior Channel (#57)

Figure 7: Grand average responses to standard (blue) and deviant (red) stimuli at representative individual channels (main condition)

Control Condition

The control condition preserved the acoustic distribution of stimuli from the main condition, but altered the distribution of stimuli at the phonological level, such that there was no longer a many-to-one ratio of voiced to voiceless consonants (or vice versa).

Based on the same statistical analyses used in the main condition, no evidence for a MMF was observed in the control condition, in either the left hemisphere ($F(1,6) = 0.01$, $p = 0.92$) or the right hemisphere ($F(1,6) = 1.39$, $p = 0.24$).

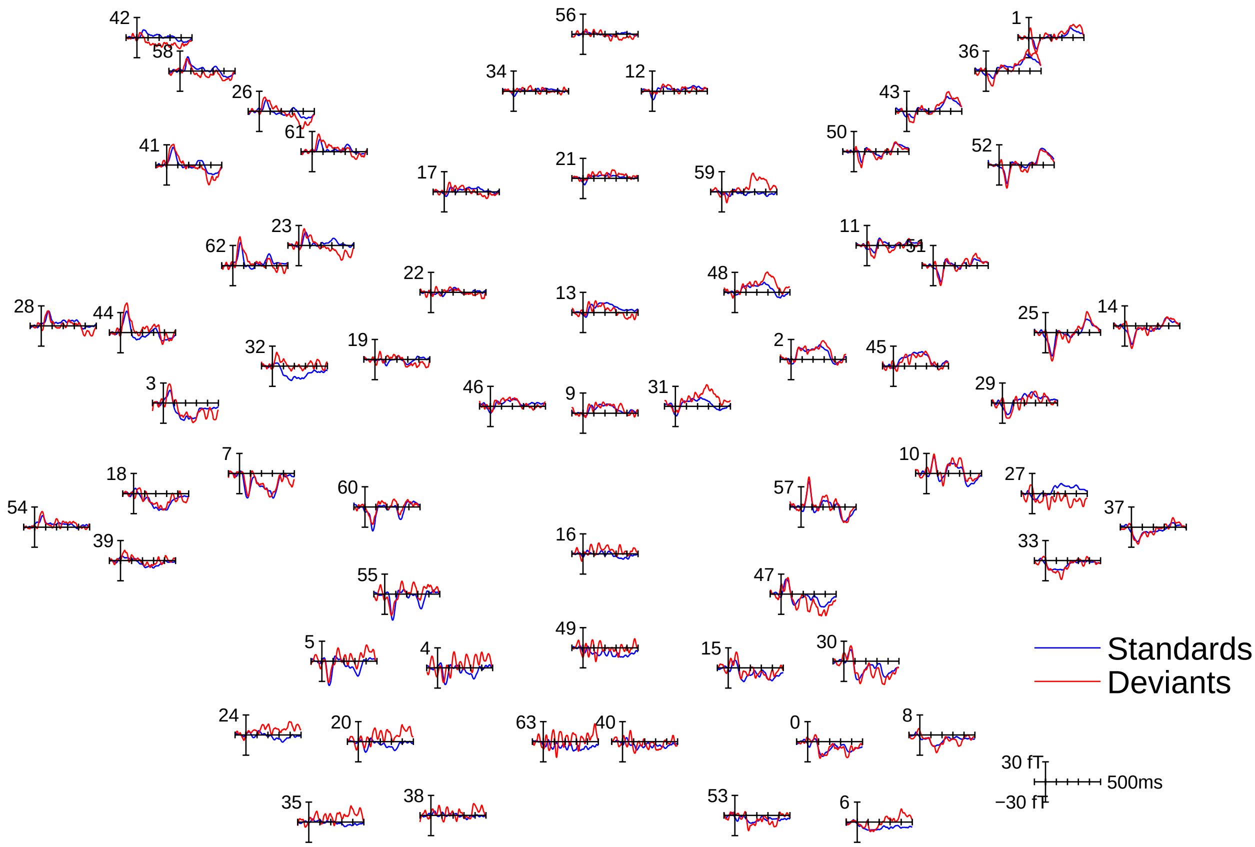
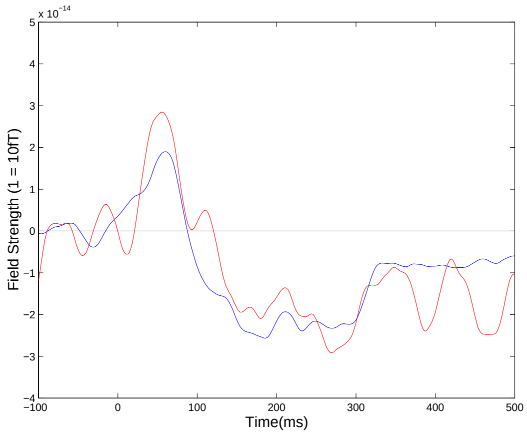
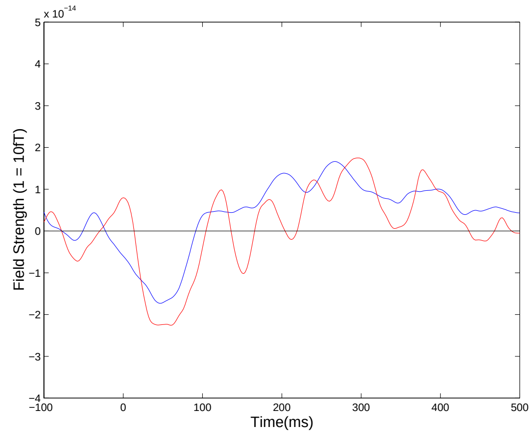


Figure 8: Grand average responses to standard (blue) and deviant (red) stimuli in control condition



Individual Left Anterior Channel (#3)



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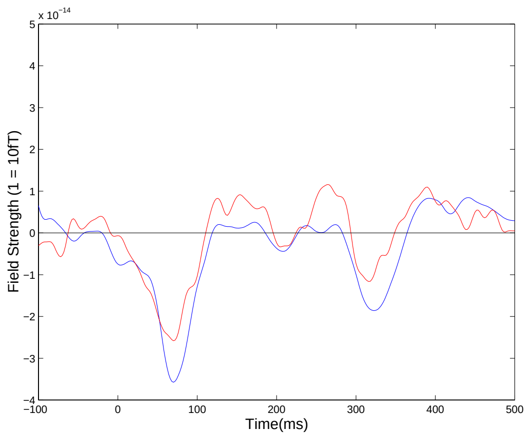
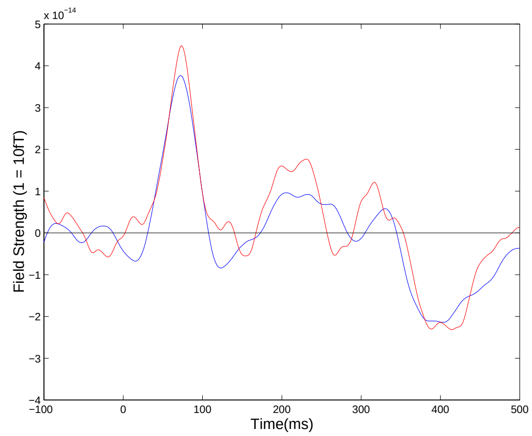


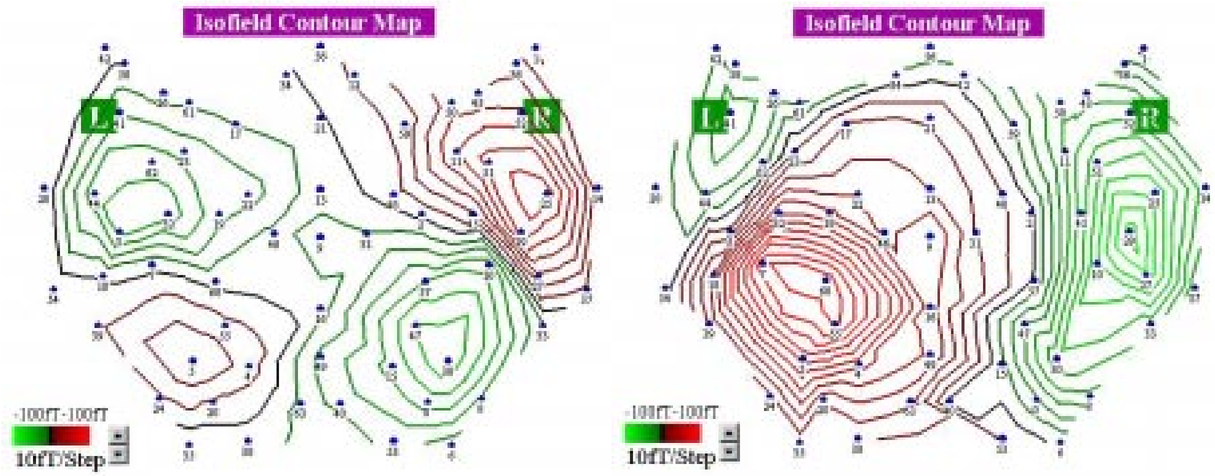
Individual Left Posterior Channel (#60)



Individual Right Posterior Channel (#57)

Figure 9: Grand average responses to standard (blue) and deviant (red) stimuli at representative individual channels (control condition)

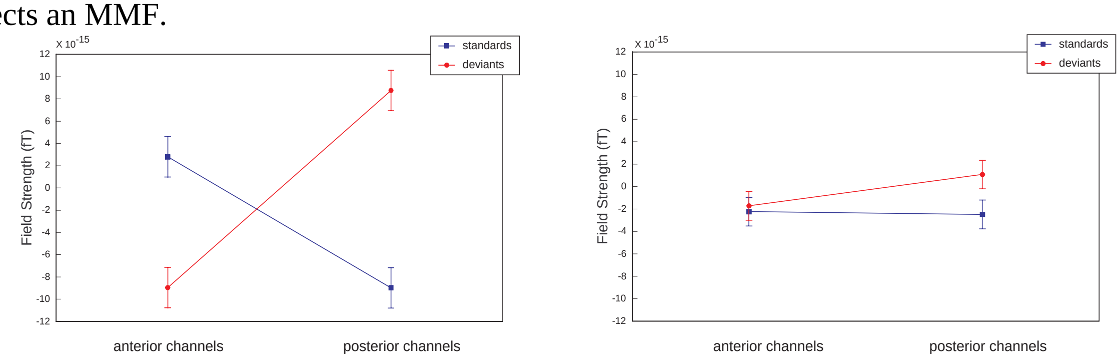
The contour map below the sensor array indicates that the MMF has a source close to the M100; the contour map also clearly shows the absence of a right hemisphere MMF.



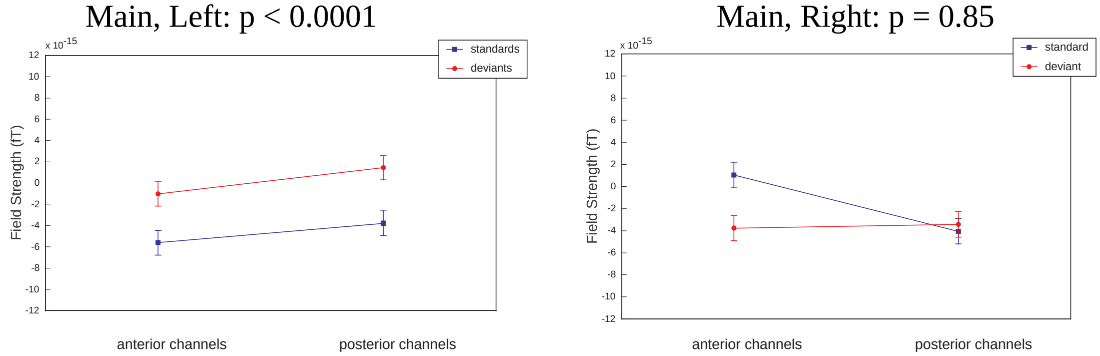
a: M100 **b:** Mismatch Field

Figure 10: Contour maps of M100 and mismatch field for one male subject

Graphs showing the relative field strength of responses to standard and deviant stimuli at groups of 5 anterior and posterior channels in each hemisphere, in the main and control conditions (150-250ms latency). The polarity reversal seen only in the left hemisphere in the main condition reflects an MMF.



Main, Left: $p < 0.0001$ Main, Right: $p = 0.85$



Control, Left: $p = 0.92$ Control, Right: $p = 0.24$

Figure 11: Channel group x stimulus-type interaction in left and right hemispheres, main and control conditions.

Our finding of a dipolar mismatch response only in the left hemisphere stands in striking contrast with a growing number of studies which report *bilateral* mismatch responses (Paavilainen et al. 1991; Näätänen & Alho, 1995; Levänen et al. 1996; Alho et al. 1998; Ackermann, Lutzenberger & Hertrich, 1999; Opitz et al. 1999), although other studies have reported hemispheric differences in the timing or amplitude of the MMF. Note that whereas all of these other studies examine acoustic or phonetic contrasts, our study examines a phonological contrast. Therefore, the strong lateralization of the MMF in our study may be due to the 'higher' level of representation tested.

Conclusion

Our experiments investigated the availability of categorial phonological representations to the generator of the auditory mismatch response. The critical property of discrete linguistic categories is that all members of the category are treated as exactly the same. In our experiments subjects listened to sequences of stimuli in which there was substantial random variability at the acoustic level, but a simple many-to-one ratio at the level of discrete phonological features.

The mismatch field observed in the main condition showed that a set of 12 acoustically different stimuli, covering 10 different voice onset time values and 3 different places of articulation (/b/, /d/, /g/) could be treated as exactly the same by the generator of the auditory mismatch field, contrasting with another set of 12 acoustically different stimuli. The fact that acoustically different stimuli are grouped in this way suggests that the MMF generator can access categorial representations of the phonological feature [±voice]. The absence of any MMF in the control condition lends further support to this interpretation. The fact that a MMF was observed only in the left hemisphere in the main condition is compatible with much evidence for left hemisphere specialization for phonological processing.

These experiments provide further evidence that the auditory mismatch paradigm, which has generally been used as a measure of auditory discrimination, can also be used as a measure of when sounds are treated as the same in higher-level representations (cf. Aulanko et al. 1993; Gomes et al. 1995).

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