ERP Evidence for Abstract Sound Categorization

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Abstract

Sound categories are abstractions over multiple acoustically different sounds. They can arise because we fail to discriminate differences among category members, but the most compelling examples of category abstraction arise when the differences are perceived but ignored. The phonologies of our native languages provide good examples of such categories, and vowels are particularly relevant, since the members of a vowel category are clearly distinguishable from one another, yet are classified into abstract categories. Most previous MMN research has focused either on discrimination rather than categorization, or on categorization of consonants, which are not readily discriminable within-category. We investigated brain responses associated with vowel categorization.

We used a grouped mismatch design, such that the "standard" and "deviant" vowels were not each a single stimulus, rather several vowels that approximate acoustically a standard and a deviant exemplar vowel. In a separate condition, pure tones varying along the same continuum were presented using an identical design. An MMN response was elicited in the vowel condition but not in the tone condition.

Background

Categorization vs. Discrimination

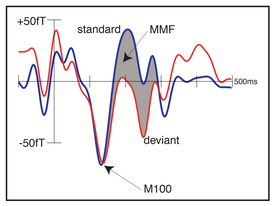
Sound categories are abstractions formed over multiple different sounds. The term 'Categorial Perception' in speech processing is commonly used to refer to either of 2 different effects:
(i) *Categorial Identification*: reliable classification of sounds as belonging to one category or another.
(ii) *Categorial Discrimination*: poor discrimination of different sounds from the same category, better discrimination across categories.
The clearest examples of abstraction arise in situations where sounds are *reliably classified, despite good within-category discrimination*. It has long been known that whereas stop consonants exhibit both categorial identification and discrimination, vowel categories exhibit categorial identification, but relatively good within-category discrimination (Fry et al., 1962).

MMN & Discriminability I: Fixed Designs

A number of MMN studies have sought effects of speech categories by exploiting categorial discrimination profiles, to test whether a fixed acoustic difference ('fixed design') between standards and deviants yields a greater MMN for between-category than for within-category contrasts. Results have been varied (cf. Näätänen et al., 1997; Maiste et al., 1995; see Phillips 2001 for review). In any case, uneven discrimination does not, on its own, provide clear evidence of abstraction.

Mismatch Response

The Mismatch Negativity (MMN) and its magnetic counterpart are elicited by infrequent 'deviant' sounds appearing in sequences of matched 'standard' sounds (Näätänen et al., 1978). A many-to-one ratio is critical to elicit the MMN. The MMN typically appears around 150-250ms post stimulus onset, and is generated in supratemporal auditory cortex (typically bilaterally).



Following some claims that the MMN is insensitive to speech category representations (e.g. Sharma et al., 1993), there have been numerous attempts to demonstrate effects of phonological categories.

MMN & Discriminability II: Grouped Designs

A smaller number of MMN studies have exploited categorial identification profiles, to test whether sequences involving multiple different tokens of standard and deviant categories manage to elicit a MMN ('grouped design'). Although these studies have found more uniform success, they have either varied category-irrelevant acoustic parameters (F0: Aulanko et al., 1993; Shestakova et al., 2002), or have tested categories that show poor within-category discrimination (voicing: Phillips et al., 2000). The current study aims to strengthen the case for access to abstract categories by using vowels, which show categorial identification and good within-category discrimination, in a grouped design.

Design

Stimuli

Stimuli were drawn from two synthetic continua. The vowel continuum ranged from /u/ to /o/, varying F1 values in 10Hz increments from 290Hz to 470Hz, while holding all other synthesis parameters constant.

The tone continuum consisted of pure tones that matched the F1 values of the vowel continuum. In order to more closely match the sounds, each pure tone was multiplied by the amplitude envelope of the corresponding synthetic vowels in the F1 range of the spectrum.

Behavioral Results

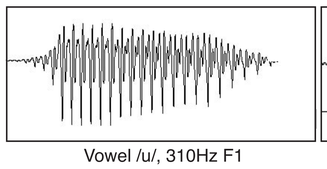
Prior to electrophysiological testing, all subjects (n=16) took part in an identification pretest, which was used to determine that individual's perceptual boundary on the /u/-/o/ continuum. Results confirmed a classic step-wise identification function.

However, a separate discrimination test confirmed that within-category discrimination is better for these vowels than for stop consonants.

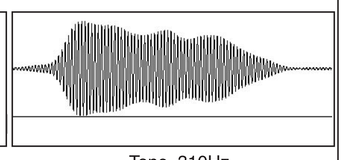
Design of ERP Study

In contrast to typical MMN studies that use a single 'standard' stimulus, stimuli in both the vowel and tone conditions consisted of multiple exemplars of each vowel category, or the corresponding tones. Sounds were drawn randomly from each stimulus group, with a 7:1 standard:deviant ratio. Subjects heard at 100 tokens of each category as deviant stimuli.

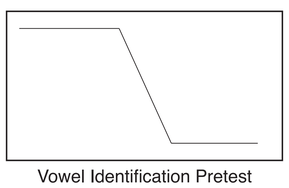
The order of tone and vowel conditions, and the order of categories as standard and deviant within each condition, were fully counterbalanced.



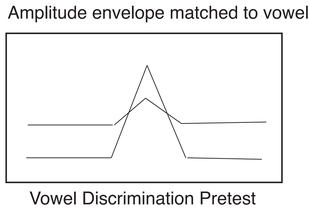
Vowel /u/, 310Hz F1



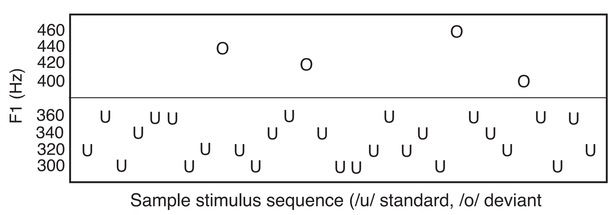
Tone, 310Hz
Amplitude envelope matched to vowel



Vowel Identification Pretest



Vowel Discrimination Pretest



Sample stimulus sequence (/u/ standard, /o/ deviant

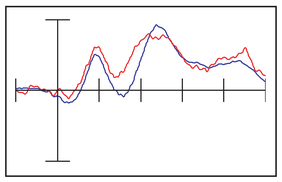
Results

Vowels

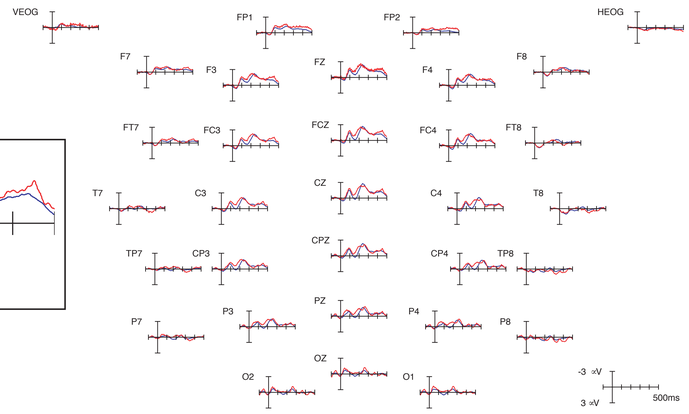
Vowel category changes elicited a clear Mismatch Negativity (MMN), with an onset in the 150-200ms time interval.

The presence of the MMN was confirmed by a repeated-measures ANOVA conducted on 12 midline and lateral electrodes. The ANOVA showed a main effect of stimulus-type (i.e. standard vs. deviant), $F(1,15) = 11.6$, $p < 0.005$, and no interaction of stimulus-type with laterality or anterior-posterior distribution.

The MMN indicates that participants formed category-based abstractions over the sequences of stimuli from the vowel continuum.



Electrode CZ

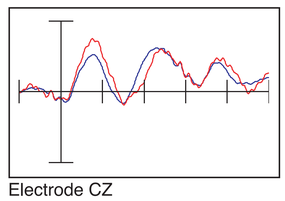


Tones

In contrast to the vowel condition, no MMN was elicited in the tone condition. The ANOVA showed no effect of stimulus-type in the 150-200ms time interval, $F(1,15) = 0.6$, $p = 0.44$.

However, at the time interval surrounding the N1 response (75-125ms), there was a marginally significant effect of stimulus-type, due to a larger amplitude N1 for deviant than for standard stimuli, $F(1,15) = 3.76$, $p = 0.72$.

We suggest that this modulation of N1 amplitude may reflect an effect of dishabituation caused by large differences between certain individual pairs of sounds, rather than an effect of category formation.



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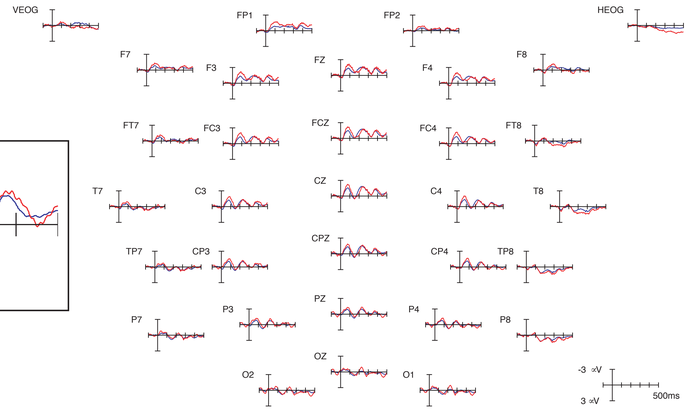

Discussion

The main finding of the study was that the contrast between responses to the vowel and tone stimuli, despite the fact that the 2 sequences of sounds varied in exactly the same fashion. In contrast to discrimination-based MMN studies, which typically show larger MMN responses to pure tone stimuli than to speech stimuli, this categorization-based MMN study showed an advantage for speech stimuli.

The design of the study has the consequence that the only way for the brain to detect a many-to-one ratio - and hence to generate a MMN - is to encode the sequence of vowel sounds in terms of phonological categories. The implication is, therefore, that the tone stimuli were not grouped into categories.

There's a clear contrast between the vowel and tone conditions. The tones show no hint of an MMN. Although N1 enhancement is sometimes observed in MMN studies that use very easy-to-discriminate contrasts, these MMN responses extend beyond the N1 interval, and generally show a larger MMN than do more subtle contrasts. Therefore, we consider it unlikely that the marginally significant N1 enhancement in the tone conditions is a form of early MMN response. Further analyses will be needed, in order to test whether this response reflects not categorization per se, but dishabituation specifically caused by large acoustic differences between certain pairs of adjacent sounds in the sequence of stimuli.

This provides improved evidence for the involvement of phonological categories in the generation of the Mismatch Negativity. Note that our conclusions would be further strengthened if it could be shown that the vowel-category MMN is not elicited in speakers of a language that fails to distinguish /u/ and /o/ phonologically (e.g. many dialects of Arabic).

Conclusion

This study provides two reinforcements to earlier claims that abstract phonological category representations are available to the auditory cortex generator of the Mismatch Negativity (MMN). First, by using vowel categories, which show relatively good within-category discrimination, it was possible to demonstrate categorization that goes beyond simple failure to discriminate. Second, by contrasting responses to sequences of vowels and tones that displayed exactly the same acoustic variation, it was possible to demonstrate that the MMN responses depended on the existence of linguistic categories.

References

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Acknowledgments

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