Behavioral and electrophysiological evidence for the impact of regional variation on phoneme perception

Brunelliere, Angèle; Dufour, Sophie; Nguyen, Noël; Frauenfelder, Ulrich Hans

How to cite

BRUNELLIERE, Angèle et al. Behavioral and electrophysiological evidence for the impact of regional variation on phoneme perception. In: Cognition, 2009, vol. 111, n° 3, p. 390–396. doi: 10.1016/j.cognition.2009.02.013

This publication URL: https://archive-ouverte.unige.ch/unige:82918

Publication DOI: 10.1016/j.cognition.2009.02.013

Cognition 111 (2009) 390–396

Contents lists available at ScienceDirect

Cognition

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

Brief article

Behavioral and electrophysiological evidence for the impact of regional variation on phoneme perception

Angèle Brunellière [a,*], Sophie Dufour [b,*,1], Noël Nguyen [b], Ulrich Hans Frauenfelder [a]

[a] Laboratoire de Psycholinguistique Expérimentale, FPSE, Université de Genève, 40, Bd du Pont d'Arve, CH 1205 Genève, Switzerland
[b] Laboratoire Parole et Langage, CNRS and Aix-Marseille University, Aix-en-Provence, France

ARTICLE INFO

Article history:
Received 6 June 2008
Revised 19 February 2009
Accepted 27 February 2009

Keywords:
Speech perception
Phonological variation
Event-related potentials
Mismatch negativity

ABSTRACT

This event-related potential (ERP) study examined the impact of phonological variation resulting from a vowel merger on phoneme perception. The perception of the /e/–/ɛ/ contrast which does not exist in Southern French-speaking regions, and which is in the process of merging in Northern French-speaking regions, was compared to the /ø/–/y/ contrast, which is stable in all French-speaking regions. French-speaking participants from Switzerland for whom the /e/–/ɛ/ contrast is preserved, but who are exposed to different regional variants, had to perform a same-different task. They first heard four phonemically identical but acoustically different syllables (e.g., /be/–/be/–/be/–/be/), and then heard the test syllable which was either phonemically identical to (/be/) or phonemically different from (/bɛ/) the preceding context stimuli. The results showed that the unstable /e/–/ɛ/ contrast only induced a mismatch negativity (MMN), whereas the /ø/–/y/ contrast elicited both a MMN and electrophysiological differences on the P200. These findings were in line with the behavioral results in which responses were slower and more error-prone in the /e/–/ɛ/ deviant condition than in the /ø/–/y/ deviant condition. Together these findings suggest that the regional variability in the speech input to which listeners are exposed affects the perception of speech sounds in their own accent.

1. Introduction

The phonology of every language shows substantial variation both across space (between different regional accents), and across time (between different generations of speakers). Nonetheless, listeners appear to adapt rather well to various accents as has been shown, for example, in a vowel categorisation task in which listeners adjust their responses to the speaker's accent in carrier phrases (Evans & Iverson, 2004). This remarkable capacity to accommodate a wide range of accents most likely results from a dynamic adjustment of the listener's phonological representations (e.g., McQueen, Norris, & Cutler, 2006). Here, we ask whether these adjustments to other accents influence the perception of speech sounds in the listener's own accent. We focus on accent-related variation associated with vowel mergers, which refer to cases in which two vowels are not, or are no longer, distinguished in pronunciation in one regional accent but remain contrastive in another accent of the same language. Our goal is to determine whether exposure to a merged variety can affect the listener's vowel perception in their unmerged native variety.

One useful way of studying vowel discrimination is by measuring the mismatch negativity (MMN) component observed in event-related potentials (ERPs). MMN is a frontocentral negative component, usually peaking at 100–250 ms from the deviation in the stimuli, which is elicited when a novel stimulus interrupts the repeated presentation of the same stimulus. This component is sensitive to changes not only in the acoustic characteristics of

* Corresponding authors.
E-mail addresses: angele.brunelliere@unige.ch (A. Brunellière), Sophie.Dufour@univ-provence.fr (S. Dufour).
[1] Laboratoire Parole et Langage, Université de Provence, 29, Avenue Robert Schuman, 13621 Aix-en-Provence, France.

0010-0277/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2009.02.013

auditory stimuli (Näätänen, Simpson, & Loveless, 1982), but also to their phonological properties (for a review, Pulvermüller & Shtyrov, 2006). For example, Näätänen and collaborators (Näätänen et al., 1997) demonstrated MMN responses to phoneme changes when Finnish listeners heard the Finnish vowel /ö/ or the unknown Estonian vowel /õ/ in a list composed predominantly of the Finnish vowel /e/. A larger MMN amplitude was found when the Finnish vowel /ö/ served as the deviant stimulus than when the unknown Estonian vowel /õ/ was presented as the deviant stimulus despite the fact that the acoustic distance of the unknown Estonian vowel /õ/ from /e/ was larger than that for the deviant Finnish vowel /ö/. Dehaene-Lambertz (1997) showed that an earlier ERP component, the P200, also reflects phonological processes. She reported significant P200 differences for acoustic tokens that were associated with different phonemic categories in the native language, but not for equidistant acoustic tokens that did not cross a native phonemic boundary. Collectively, these results suggest that both P200 and MMN reflect processes that involve phonemic representations, and that responses earlier than the MMN can be generated by a phonemic change.

In the only electrophysiological study on vowel mergers known to us, Conrey, Potts, and Niedzielski (2005) compared the perception of minimal pairs of words with an /I/–/ɛ/ vowel contrast (e.g., *pin*/*pen*). Although these authors failed to observe differences in MMN response between merged and unmerged speakers, they did obtain differences in a late positivity component (LPC) which they attributed to conscious phonological decision processes. Interestingly, the unmerged speakers were able to discriminate less well between word pairs contrasting in merging vowels than between control pairs of words like *pain*/*pin*. Conrey et al. (2005) put forward two alternative explanations for these findings. According to the first, exposure to vowel mergers occurring in other regional accents leads to poorer discrimination of merging vowels by unmerged speakers. The second referred to the potentially greater acoustic similarity between the merging vowels than between the control vowels. In our study, we have attempted to disentangle these two potential explanations by examining the performance of unmerged speakers in discriminating two contrasts that are equally similar acoustically, one involving merging vowels and the other involving vowels unaffected by a merger.

An example of a vowel merger in French is provided by the /e/–/ɛ/ contrast. Whereas Standard French is traditionally said to establish a contrastive distinction between /e/ and /ɛ/ in word-final open syllables (e.g., *épée* "sword" /epe/ vs. *épais* "thick" /epɛ/), this distinction does not exist in Southern French, which only has close-mid /e/ in that position (Fagyal, Kibbee, & Jenkins, 2006). Thus, both *épée* and *épais* are pronounced /epe/ in this regional variety. Furthermore, Fagyal, Hassa, and Fallou (2002) provided evidence suggesting that the /e/ and /ɛ/ vowels are undergoing a merger process in some young speakers of Parisian French who only produce the close-mid variant /e/ in word-final open syllables.

In this ERP experiment, we compared the neural responses to the perception of the /e/–/ɛ/ contrast which is subject to regional variations in French-speaking regions with that of the /ø/–/y/ contrast, a stable phonemic contrast in French. The /ø/–/y/ contrast was chosen as a basis of comparison because as for the /e/–/ɛ/ contrast, the critical vowels differ by only one phonetic feature (i.e., vowel height). Swiss French participants from Geneva for whom the /e/–/ɛ/ opposition is preserved (Dufour, Nguyen, & Frauenfelder, 2007; Schouwey, 2008), but who are often exposed to variable pronunciations of words containing /e/ and /ɛ/ via the media or their interactions with speakers from other French-speaking regions, had to perform a same–different task. They first heard four phonemically identical but acoustically different syllables (e.g., /be/–/be/–/be/–/be/), which were produced by four different female speakers, and then heard the test syllable which was produced by a male speaker and which was either phonemically identical (control condition, /be/) or phonemically different (deviant condition, /bɛ/) from the preceding context stimuli (see also for a similar procedure, Dehaene-Lambertz, Dupoux, & Gout, 2000). As suggested in the literature (Dehaene-Lambertz et al., 2000; Eulitz & Lahiri, 2004; Phillips, 2001) the variability introduced by mixing speakers forces the participant to rely on more abstract representations and therefore allows us to examine phonological processing.

2. Materials and methods

2.1. Participants

Fourteen right-handed French-speaking students from the University of Geneva (handedness assessed using the Edinburgh Inventory) participated in the experiment for course credits after having given written informed consent. All participants reported having no neurological or hearing impairment. Their error rate in the same–different task was under 20%.

2.2. Materials

Five French speakers (four female, one male) produced four syllables (/be/, /bɛ/, /bø/ and /by/) several times. The best tokens for each speaker were selected as experimental stimuli. By means of visual and auditory inspection using a speech signal editor, we selected the test syllables (/be/, /bɛ/, /bø/ and /by/) produced by the male speaker that were best matched in fundamental frequency and amplitude envelope. All syllables were adjusted to have the same total duration of 170 ms (50 ms of prevoicing and 120 ms of plosion and vowel).

We measured the average euclidean distance in the F1–F2 plane between the four context syllables and the test syllable at the acoustic mid-point of the vowel: for /be/–/bɛ/: 2.09 Barks; for /bɛ/–/be/: 1.77 Barks; and for /bø/–/by/: 1.51 Barks; for /by/–/bø/: 2.75 Barks. These acoustic measures showed that overall the average distance between the context and test vowels was not greater for /ø/–/y/ than /e/–/ɛ/. Further analyses were conducted using the computational Auditory Image model of peripheral auditory processing (Patterson, Allerhand, & Giguère,

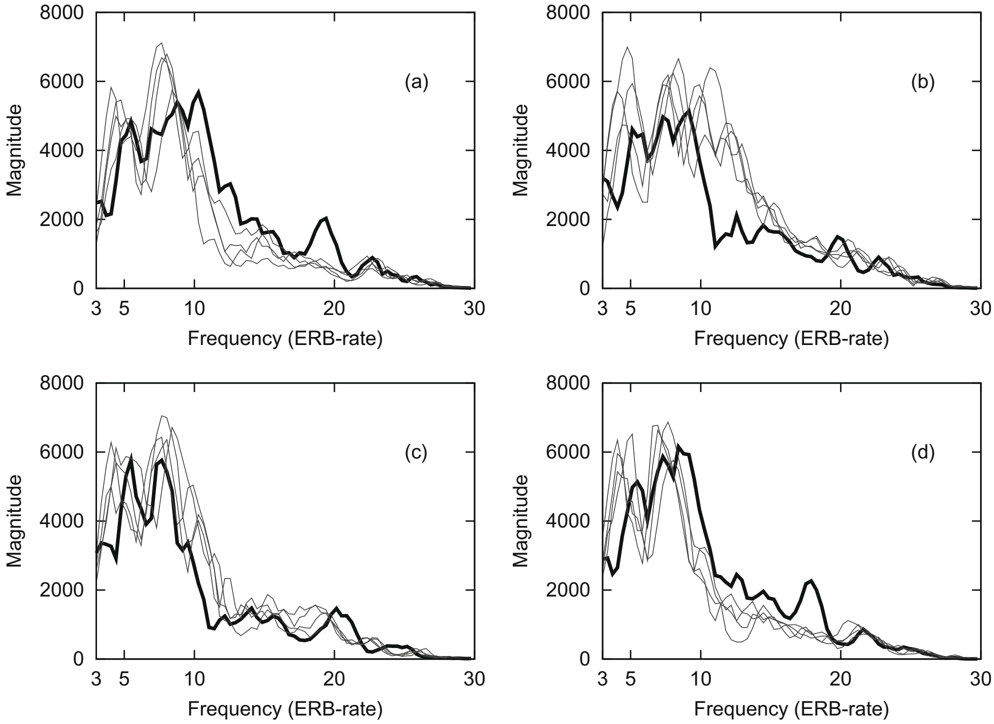

Fig. 1. Auditory spectral profiles associated with the context (grey lines) and test (dark line) syllables, as computed in the vicinity of the vowel nucleus' acoustic mid-point using Patterson et al.' s (1995) computational Auditory Image model. (a) /be/ (context)–/bɛ/ (test); (b) /bɛ/ (context)–/be/ (test); (c) /bø/ (context)–/by/ (test); and (d) /by/ (context)–/bø/ (test).

1995) which simulates the activity that complex sounds elicit in the auditory pathways. An auditory spectral profile was computed in the vicinity of the vowel's acoustic mid-point for each syllable as produced by each speaker. The average euclidean distance (calculated across the 200–2500 Hz frequency range) between the auditory spectral profiles associated with the context vowel, on the one hand, and the test vowel on the other hand, revealed that /ø/–/y/ did not differ from each other to a greater extent than /e/–/ɛ/ (see Fig. 1).

2.3. Procedure

Stimuli were presented binaurally via headphones in an acoustically shielded chamber. Trials consisted of five syllables, each separated from the following one by 600 ms of silence. On any given trial, the first four context stimuli were all phonemically identical (e.g., all /be/s), but spoken by four different female speakers. The order of the female voices was counterbalanced across the trials. The fifth and final stimulus, the test syllable, always produced by the male speaker, was either the same as (control condition), or different from (deviant condition) the first four context syllables. The experimental conditions are illustrated in Table 1. Eighty trials were presented per experimental condition, producing 320 trials which were presented randomly. Participants were instructed to indicate as quickly and accurately as possible whether the test syllable was the same syllable as or a different syllable from the preceding context by making a bimanual response. The response buttons were counterbalanced across participants. Reaction times (RTs) were measured from the onset of the test syllable. An inter-trial interval of 3000 ms elapsed between the end of one trial and the beginning of the next. Participants first received 16 practice trials and then two blocks of 160 experimental trials separated by a short break.

2.4. Recording system

The electroencephalogram (sample rate 1024 Hz) was recorded from the scalp with a 64-channel BioSemi Active-Two AD-box. Individual electrodes were adjusted to a stable offset of <20 mV. The EEG epochs, starting at 100 ms before test syllables and ending 500 ms after these syllables, were averaged for each experimental condition and for each participant. The EEG data were filtered offline by a bandpass (0.7–20 Hz) and corrected by a baseline[2] of 100 ms before the test syllable onset. Epochs were accepted under an artefact rejection criterion of 70 μV. All participants in this study had a number of accepted trials superior to 50 for each experimental condition. The epochs made for each experimental condition and for each participant were calculated independently of whether the behavioral responses were correct or incorrect. Data from bad channels for each participant were interpolated (Perrin, Pernier,

[2] An additional statistical analysis was computed on the time window of the baseline correction. It revealed no significant effects for any of the factors.

Table 1
Stimuli used in four within-participant experimental conditions.

		Context syllables produced by the female speakers	Test syllable produced by the male speaker
/ø/–/y/ contrast	Control condition	/bø/–/bø/–/bø/–/bø/	/bø/
		/by/–/by/–/by/–/by/	/by/
	Deviant condition	/bø/–/bø/–/bø/–/bø/	/by/
		/by/–/by/–/by/–/by/	/bø/
/e/–/ε/ contrast	Control condition	/be/–/be/–/be/–/be/	/be/
		/bε/–/bε/–/bε/–/bε/	/bε/
	Deviant condition	/be/–/be/–/be/–/be/	/bε/
		/bε/–/bε/–/bε/–/bε/	/be/

Bertrand, Giard, & Echallier, 1987) and the EEG signal was transformed using the average reference.

2.5. Data analysis

Analyses of variance (ANOVA) were conducted on the error rates and on the RTs with phonemic contrast (/e/–/ε/ vs. /ø/–/y/) and condition (control vs. deviant) as variables. To assess the timing of differential ERP responses between the two phonemic contrasts across the conditions, an ANOVA was also computed around each ERP component, with the following factors: phonemic contrast (/e/–/ε/ vs. /ø/–/y/), condition (deviant vs. control) and sites (frontocentral, centroparietal, left temporal, right temporal, left posterior and right posterior). Three time windows were selected around the peak amplitude of the three components identified: 73–113 ms (N100), 190–230 ms (P200) and 270–310 ms (MMN). A late time window between 372 and 486 ms after the onset of test syllable was also used to analyse later effects. The scalp surface was divided into six groups of six electrodes each: frontocentral (F1, Fz, F2, FC1, FCz and FC2), centroparietal (CP1, CPz, CP2, P1, Pz and P2), left temporal (AF7, F7, F5, FT7, T7 and AF3), right temporal (AF8, F6, F8, FT8, T8 and AF4), left posterior (TP7, CP5, CP3, P7, P5 and P3) and right posterior (TP8, CP6, CP4, P8, P6 and P4). The Greenhouse–Geisser correction was applied (Greenhouse & Geisser, 1959) and the corrected p values are reported below.

3. Results

3.1. Behavioral results

The analysis of error rates showed a significant phonemic contrast × condition interaction ($F(1,13) = 23.44$, $p < 0.001$). For each condition, planned comparisons on the error rates between each phonemic contrast were made. In the control condition, performance was identical for the /e/–/ε/ and /ø/–/y/ contrasts (3% errors for each contrast, $F(1,13) = 0.1$, $p > 0.2$). Unlike the control condition, there were more errors for the /e/–/ε/ contrast (8%) than for the /ø/–/y/ contrast (1%) in the deviant condition ($F(1,13) = 36.49$, $p < 0.001$).

As with the errors, a phonemic contrast × condition interaction ($F(1,13) = 23.35$, $p < 0.001$) was also observed on RTs. Whereas no difference on RTs was found in the control condition between the /e/–/ε/ contrast (730 ms) and the /ø/–/y/ contrast (708 ms) ($F(1,13) = 2.35$, $p = 0.15$), participants were much slower for the /e/–/ε/ contrast (837 ms) than for the /ø/–/y/ contrast (702 ms) in the deviant condition ($F(1,13) = 28.06$, $p < 0.001$), again suggesting that the /e/–/ε/ contrast is more difficult to discriminate than the /ø/–/y/ contrast.

3.2. EEG results

Grand-average waveforms of each phonemic contrast in the two conditions are displayed in Fig. 2. In all conditions, a negative wave, the N100, classically associated with acoustical processing, appears with a maximum amplitude peak around 93 ms. The N100 was followed by a P200 with maximum amplitude located at centroparietal recording sites and a second negative wave which had maximum amplitude at frontocentral recording sites similar to the topography of MMN component (see Fig. 3).

On the N100 time window, differences on sites ($F(5,65) = 16.5$, $p < 0.001$) only were observed. Centroparietal and frontocentral recording sites had more negative values than the other four recording sites ($p < 0.01$), and frontocentral recording sites appeared to be more negative than centroparietal sites ($p < 0.05$), corresponding to the classic topography of N100.

On the P200 time window, a trend effect of condition ($F(1,13) = 4.06$, $p = 0.06$) was observed with more negative values in the control than in the deviant condition. As electrodes placed around at Cz are usually used for studying the P200 (e.g., Breznitz, 2007) centroparietal recording sites were analysed for this time window. Interestingly, a significant phonemic contrast × condition interaction ($F(1,13) = 4.59$, $p = 0.05$) was found. For the /ø/–/y/ contrast, more positive values were observed in the control than in the deviant condition ($F(1,13) = 10.2$, $p < 0.01$). In contrast, no effect of condition was observed for the /e/–/ε/ contrast.

On the MMN time window, a significant condition × sites interaction ($F(5,65) = 3.23$, $p = 0.05$) was found. More negative values for the deviant than for the control condition at frontocentral recording sites ($F(1,13) = 5.24$, $p < 0.05$) were found along with more negative values for the control condition at left temporal recordings sites ($F(1,13) = 8.98$, $p < 0.05$). Moreover, centroparietal recording sites tended to show more positive values for the control than for the deviant condition ($F(1,13) = 4.33$, $p = 0.06$). No interaction between phonemic contrast and condition on any site was found.

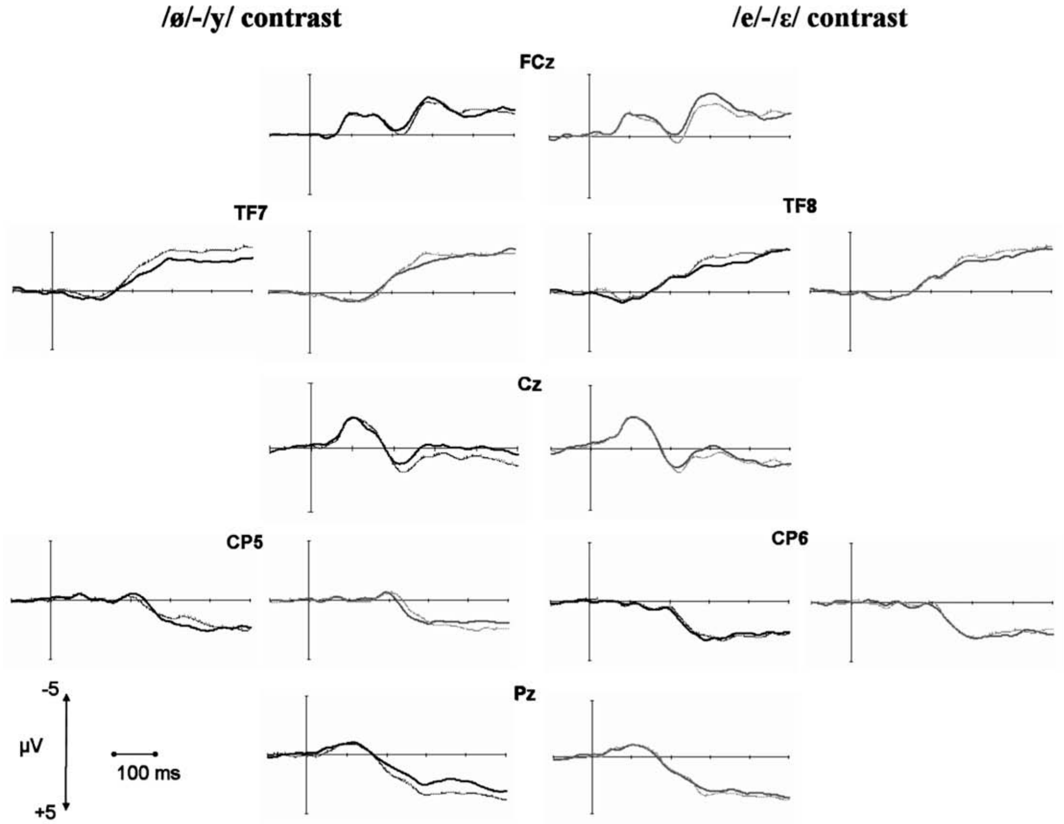

Fig. 2. Grand-average waveforms at various recordings sites obtained for the /ø/–/y/ (left) and /e/–/ɛ/ (right) contrasts. ERPs to the control condition are in grey line and those to deviant condition in black line.

As we used the same design as Dehaene-Lambertz et al. (2000), and as the authors reported a late effect of conscious detection on temporal and centroparietal sites, we analysed these particular regions in a late time window. A significant phonemic contrast × condition interaction, although limited to the left temporal sites, was found ($F(1,13) = 6.31$, $p < 0.05$). The /ø/–/y/ contrast elicited more negative values for the control condition ($F(1,13) = 7.1$, $p < 0.05$) whereas no effect of condition was observed for the /e/–/ɛ/ contrast.

4. Discussion

Our study compared behavioral and electrophysiological measures for the processing of a vowel contrast, /e/–/ɛ/, which does not exist in Southern French and which is disappearing in young speakers of Northern French, with the /ø/–/y/ contrast, which is stable in French. Results showed clear processing differences between the two contrasts. In particular, the /e/–/ɛ/ contrast induced only an MMN, while the /ø/–/y/ contrast elicited not only an MMN but also significant electrophysiological differences between control and deviant conditions on the P200. Note that an additional analysis including the components (MMN vs. P200) as a factor showed a significant phonemic contrast × component interaction ($F(1,13) = 8.22$, $p < 0.05$), which reinforces the claim that the two contrasts lead to differential processing, particularly in the P200 time window. The observed differences on the P200 suggest that the /ø/–/y/ contrast is discriminated earlier and so more easily than the /e/–/ɛ/ contrast, an observation also reflected by the lack of late differences, generally attributed to conscious level, for the /e/–/ɛ/ contrast.[3] Collectively, these ERP findings are in line with the behavioral data showing that responses were slower and more error-prone in the /e/–/ɛ/ deviant condition than in the /ø/–/y/ deviant condition.

On the basis of our acoustic analyses of the stimuli and the specific experimental design used, we can conclude that the observed effects are phonemic and not acoustic in nature. Our analyses clearly suggest that the acoustic distance between the non-merging vowels /ø/ and /y/ in an acoustic-auditory space was not greater than between the merging contrast. Moreover, our use of different speakers in the context and the change in the sex of the speakers between the context and the test syllable encouraged participants to rely upon an abstract representation to make their decision (see also Dehaene-Lambertz et al., 2000; Eulitz & Lahiri, 2004; Phillips, 2001).

[3] The absence of a comparable late effect of condition for the /e/–/ɛ/ contrast could be due to our choice of time windows for the ERP analysis. Effects may arise for this contrast after the end of our time window. However, we chose to limit this time window so as to avoid introducing motor preparation and response execution effects into our results.

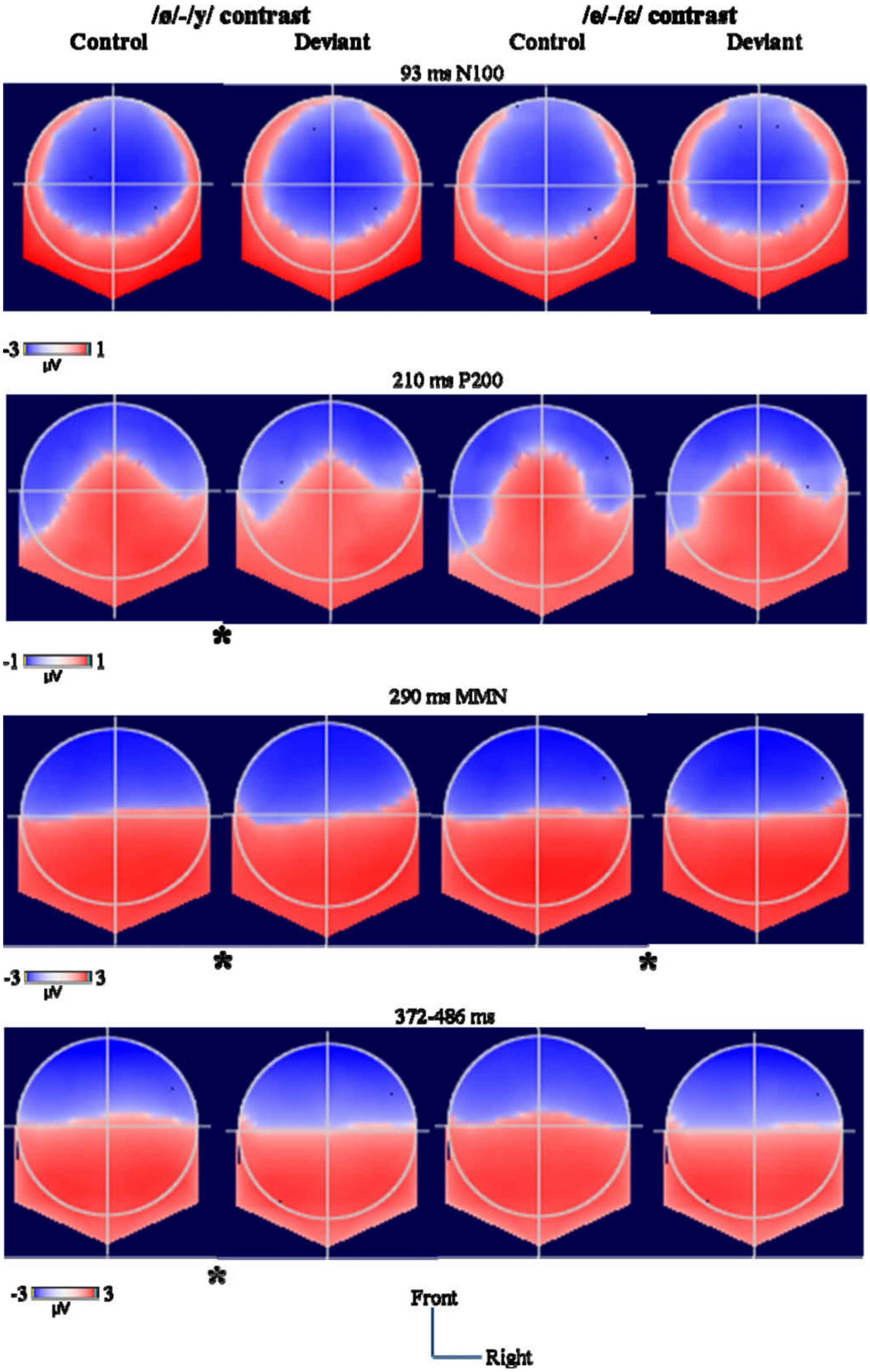

Fig. 3. Topography of the grand-average of ERPs to test syllables in each condition for each phonemic contrast at the maximum peak of each component and at the late time window. $^*p \leqslant 0.05$ for the main effect of condition for at least one recording site.

How might we account for our participants' greater difficulty in discriminating between vowels which are in the process of merging? There is some evidence (Shestakova, Brattico, Soloviev, Klucharev, & Huotilainen, 2004) which suggests the existence of a phonemotopic map in the Perisylvian regions which selectively responds to each vowel occurring in a particular language. For example, Obleser and collaborators (Obleser, Elbert, Lahiri, & Eulitz, 2003) recorded the magnetic responses to the /a/, /e/ and /i/ German vowels and found more widely separated source locations for the most dissimilar vowels /a/ and /i/. Hence, one possible way to account for our results is to postulate that, due to the greater variability of the /e/–/ɛ/ contrast across regions and speakers in French, the /e/ and /ɛ/ vowels have memory traces that are close together in the phonemotopic map, thus making their discrimination more difficult.

To sum up, our results point to poorer phonemic discrimination for vowels which are in the process of merging in French and this even for listeners who preserve this vowel contrast (Dufour et al., 2007). The regional variability in the speech input to which listeners are exposed thus influences the perception of vowels in their own regional accent. Hence it appears that the listeners' remarkable capacity to accommodate a wide range of accents as demonstrated in recent studies (e.g., Kraljic, Brennan, & Samuel, 2008) does not come without a cost in processing vowels in their own accent.

Acknowledgements

This work was supported by the TCAN Interdisciplinary CNRS Program, the FNRS Grant 105311-109987/1, and the ANR Grant ANR-08-BLAN-0276-01. The data analysis was performed using Cartool Software (Center for Biomedical Imaging of Geneva and Lausanne). Our thanks go to Christoph Michel and Thierry Legou for useful discussions and to Vincent Aubanel for his help with the acoustic analyses. We are grateful to three anonymous reviewers for their helpful comments on earlier versions.

References

Breznitz, Z. (2007). *Brain research in language*. Springer-Verlag New York Inc.
Conrey, B., Potts, G. F., & Niedzielski, N. A. (2005). Effects of dialect on merge perception: ERP and behavioral correlates. *Brain and Language, 95*, 435–449.
Dehaene-Lambertz, G. (1997). Electrophysiological correlates of categorical phoneme perception in adults. *Neuroreport, 8*, 919–924.
Dehaene-Lambertz, G., Dupoux, E., & Gout, A. (2000). Electrophysiological correlates of phonological processing: A cross-linguistic study. *Journal of Cognitive Neuroscience, 12*, 635–647.
Dufour, S., Nguyen, N., & Frauenfelder, U. H. (2007). The perception of phonemic contrasts in a non-native dialect. *Journal of Acoustical Society of America, 121*, EL131–EL136.
Eulitz, C., & Lahiri, A. (2004). Neurobiological evidence for abstract phonological representations in the mental lexicon during speech recognition. *Journal of Cognitive Neuroscience, 16*, 577–583.
Evans, B. G., & Iverson, P. (2004). Vowel normalization for accent: An investigation of best exemplar locations in northern and southern British English sentences. *Journal of the Acoustical Society of America, 115*, 352–361.
Fagyal, Z., Hassa, S., & Fallou, N. (2002). L'opposition [e]–[ɛ] en syllabes ouvertes de fin de mot en français parisien: Étude acoustique préliminaire. In *Proceedings of the XXIVth Journées d'Études sur la Parole, Nancy, France* (pp. 165–168). 24–27 June 2002.
Fagyal, Z., Kibbee, D., & Jenkins, F. (2006). *French: A linguistic introduction*. Cambridge, UK: Cambridge University Press.
Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika, 24*, 95–111.
Kraljic, T., Brennan, E. B., & Samuel, A. G. (2008). Accommodating variation: Dialects, idiolects, and speech processing. *Cognition, 107*, 54–81.
McQueen, J. M., Norris, D., & Cutler, A. (2006). The dynamic nature of speech perception. *Language and Speech, 49*, 101–112.
Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., et al. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature, 385*, 432–434.
Näätänen, R., Simpson, M., & Loveless, N. E. (1982). Stimulus deviance and evoked potentials. *Biological Psychology, 14*, 53–98.
Obleser, J., Elbert, T., Lahiri, A., & Eulitz, C. (2003). Cortical representation of vowels reflects acoustic dissimilarity determined by formant frequencies. *Brain Research: Cognitive Brain Research, 15*, 207–213.
Patterson, R. D., Allerhand, M. H., & Giguère, C. (1995). Time-domain modeling of peripheral auditory processing: A modular architecture and a software platform. *Journal of the Acoustical Society of America, 98*, 1890–1894.
Perrin, F., Pernier, J., Bertrand, O., Giard, M. H., & Echallier, J. F. (1987). Mapping of scalp potentials by surface spline interpolation. *Electroencephalography and Clinical Neurophysiology, 66*, 75–81.
Phillips, C. (2001). Levels of representation in the electrophysiology of speech perception. *Cognitive Science, 25*, 711–731.
Pulvermüller, F., & Shtyrov, Y. (2006). Language outside the focus of attention: The mismatch negativity as a tool for studying higher cognitive processes. *Progress in Neurobiology, 79*, 49–71.
Schouwey, V. (2008). Les variantes cantonales dans la prononciation des voyelles du français en Suisse romande. Unpublished master's thesis. Switzerland: University of Geneva.
Shestakova, A., Brattico, E., Soloviev, A., Klucharev, V., & Huotilainen, M. (2004). Orderly cortical representation of vowel categories presented by multiple exemplars. *Brain Research: Cognitive Brain Research, 21*, 342–350.