A phonological representation in the infant brain

IN adults, neural networks for phonological processing distinct from those involved in acoustical processing are located in the left temporal lobe. We now report that by the age of 3 months, infants display phonological processing devices analogous to those found in adults. Within a stream of identical syllables, acoustic deviants were introduced, either crossing a phonetic boundary or remaining within the same category. Event-related potentials were recorded using a 64-electrode net. Although the acoustical change was of similar amplitude in the two deviants, the electrophysiological response was larger for a phonological change and involved a more posterior and dorsal temporal region than for an acoustical change. These results demonstrate that infants, like adults, already possess a dedicated neuronal network for phonetic processing. *NeuroReport* **9**: 1885–1888 © 1998 Rapid Science Ltd.

G. Dehaene-Lambertz[CA] and S. Baillet[1]

Laboratoire de Sciences Cognitives et Psycholinguistique (CNRS URA 1198), 54 boulevard Raspail, 75270 Paris 06, and Service de Neuropédiatrie, Centre Hospitalier Universitaire Bicêtre; [1]Laboratoire de Neurosciences Cognitives et Imagerie Cérébrale (CNRS UPR 640), CHU Pitié Salpetrière, Paris, France

[CA]Corresponding Author

Introduction

Phoneme perception, contrary to the perception of many other sounds, is categorical: an acoustical change is perceived only if it crosses a phoneme boundary. Moreover, phoneme representation is language-specific, and adults sometimes have difficulty in discriminating non-native phonetic contrasts:[1] for example the Japanese cannot distinguish the /r/ /l/ contrast.[2] Using event-related potentials (ERP) it has been demonstrated that this categorization process takes place very early in signal processing and that sensory memory contains a phoneme representation in addition to one for the acoustical features of the stimulus.[3,4] An electrophysiological component, mismatch negativity (MMN), is generated when a mismatch occurs between the features of a novel stimulus and the neural traces of the preceding sound. Dehene-Lambertz[3] showed that for an equal acoustic distance between the deviant and the previous syllables, the MMN is dependent on the linguistic relevance of the syllable change in the subjects' native language. For example, she observed no MMN for a Hindi phonetic contrast in French adults while a MMN is present for a similar acoustical change that crosses a French phonetic boundary. Näätänen and his colleagues[4] demonstrated that the MMN is significantly reduced when adults hear an acoustic change that does not signal a phoneme boundary relevant to their native language, in comparison to a change that crosses a native phoneme boundary.

Using magnetoencephalography, these authors showed that the phonemic representation is based on a neural network predominantly located in the left temporal lobe, and distinct from that involved in acoustical processing.

How and when do these phonemic networks develop in the infant brain? Using high-amplitude sucking, Eimas *et al.*[5] demonstrated that categorical perception is present in 1-month-old infants. Dehaene-Lambertz and Dehaene[6] showed that, at 2 months of age, a specific electrophysiological response occurs after about 400 ms following the introduction of a single novel syllable in a stream of identical syllables. The voltage topography suggests that this response originates from the temporal lobes, with a larger response from the left hemisphere. It remained unclear, however, whether this response reflects the activation of an acoustical discrimination process or of a dedicated phonological perception system similar to the adult system.[7] In the present experiment, we studied high-density event-related potentials in 3-month-old infants while they were listening to two acoustical changes of similar amplitude that did or did not cross a native phonetic boundary.

Materials and Methods

Three syllables S1, S2 and S3 (275 ms duration, 69 dB SPL intensity) were synthesized at equal intervals along a voiced place of articulation continuum.[8]

English and French adults perceived S1 and S2 as belonging to the same phoneme category, and S3 as belonging to a different category. Each trial comprised four syllables (stimulus onset asynchrony 600 ms, intertrial interval 4 s). Three trial types were randomly presented (40 trials per condition). On control trials (CO) S2 was repeated four times. On within-category trials (WC) S2 was preceded by three repetitions of S1. Finally on across-category trials (AC), S2 was preceded by three repetitions of S3. We thus analysed the evoked response to the same syllable S2 in different contexts. We reasoned that acoustical processes should detect a mismatch on both WC and AC trials, whereas phonological processes should show a specific response to novelty on AC trials only. Indeed, French adults tested in this situation detected a change in 4.8% of the CO trials, 12.8% of the WC trials and 81% of the AC trials, and their evoked response showed the predicted AC-specific mismatch response,[3] analogous in topography to that observed by Näätänen et al.[4]

Twenty-four French infants (mean age 111 days, range 103–130 days) were tested after parents gave written informed consent. Eleven additional infants were rejected: three fell asleep during the experimental run and eight had less than 20 artefact-free trials. In order to keep the infants quiet during the experimental run, attractive visual stimuli were presented on a computer screen independently of the auditory stream. ERP were collected using a 64-channel geodesic electrode net referenced to the vertex, and digitized at 125 Hz over a 3072 ms epoch including a 150 ms baseline. Trials contaminated by eye or motion artifacts were automatically rejected. For each subject and each condition, the remaining trials (average 49.2 trials/infant) were averaged, baseline corrected, transformed to an average reference and digitally filtered (band pass 0.5–20 Hz). Two-dimensional reconstructions of scalp voltage at each time were computed using spherical sline interpolation.[9]

Results

As previously described,[6] the evoked response to each syllable comprised two peaks that decreased in amplitude with repetition, and the introduction of a new syllable induced a recovery of the amplitude of peak 2, but not of peak 1, relative to control trials (Fig. 1). This recovery, however, was greater on AC trials than on WC trials. Furthermore, its topography differed. On electrodes at or in front of the vertex, similar reactions were found to both WC and AC changes. On left and right frontal electrodes, a response to change was found only on AC trials,

and hence only when the acoustical change signalled a phoneme boundary (Fig. 1).

For statistical analyses, four successive time windows of 80 ms (160–480 ms after syllable onset) were selected. These time windows included peaks 1 and 2, whose maxima were at 240 and 400 ms, respectively. The inspection of the time course of two-dimensional reconstructions of t-test values in the comparison of each deviant with control trials isolated three clusters of electrodes where statistical differences were significant: a frontal site including seven electrodes on each side, an occipital site including four electrodes on each side, and a vertex site including the vertex and the four surrounding electrodes.

The evolution of the evoked response to the three first identical syllables was analysed at the frontal and the occipital sites. Two repeated-measures analyses of variance (ANOVA) were performed on voltage averaged over each site during each of the four time windows with stimulus number (syllabus 1–3) and hemisphere (left, right) as factors. On each time window and for the two locations, there was a main effect of stimulus number ($p < 0.001$), due to a significant decrease in voltage between syllables 1 and 2 ($p < 0.003$). There was a main effect of hemisphere only on the frontal location and for the two time windows including peak 2 (320–400 ms window: $F(1,23) = 7.3$, $p = 0.012$; 400–480 ms window: $F1(1,23) = 4.7$, $p = 0.041$) indicating higher voltage over the left hemisphere, with no significant interaction of hemisphere with stimulus number ($p > 0.05$).

To analyse the effect of deviance, two repeated-measures analyses of variance (ANOVA) were performed on voltage averaged over the frontal and occipital sites during the same four successive time windows for the fourth syllable, with condition (control, within-category change and across-category change) and hemisphere as factors. The vertex site was analysed with the same parameters as the other two sites, except for the hemisphere factor.

In ANOVAs over left and right frontal as well as the vertex site, significant effects of trial type (CO, WC or AC) were found only in the fourth time window (400–480 ms). At the vertex site, there was a main effect of trial type ($F(2,46) = 4.1$, $p = 0.023$) with a significant difference between AC and CO ($F(1,23) = 6.0$, $p = 0.022$) and between WC and CO ($F(1,23) = 9.0$, $p = 0.006$), but not between AC and WC ($F < 1$) thus, reflecting acoustical mismatch detection. At the frontal site, there was also a main effect of trial type ($F(2,46) = 6.1$, $p = 0.004$) with a significant difference between AC and CO ($F(1,23) = 11.5$, $p = 0.002$). However on this site, WC did not differ from CO ($F < 1$) while AC differed from WC ($F(1,23) = 7.4$, $p = 0.012$), reflecting the response of a
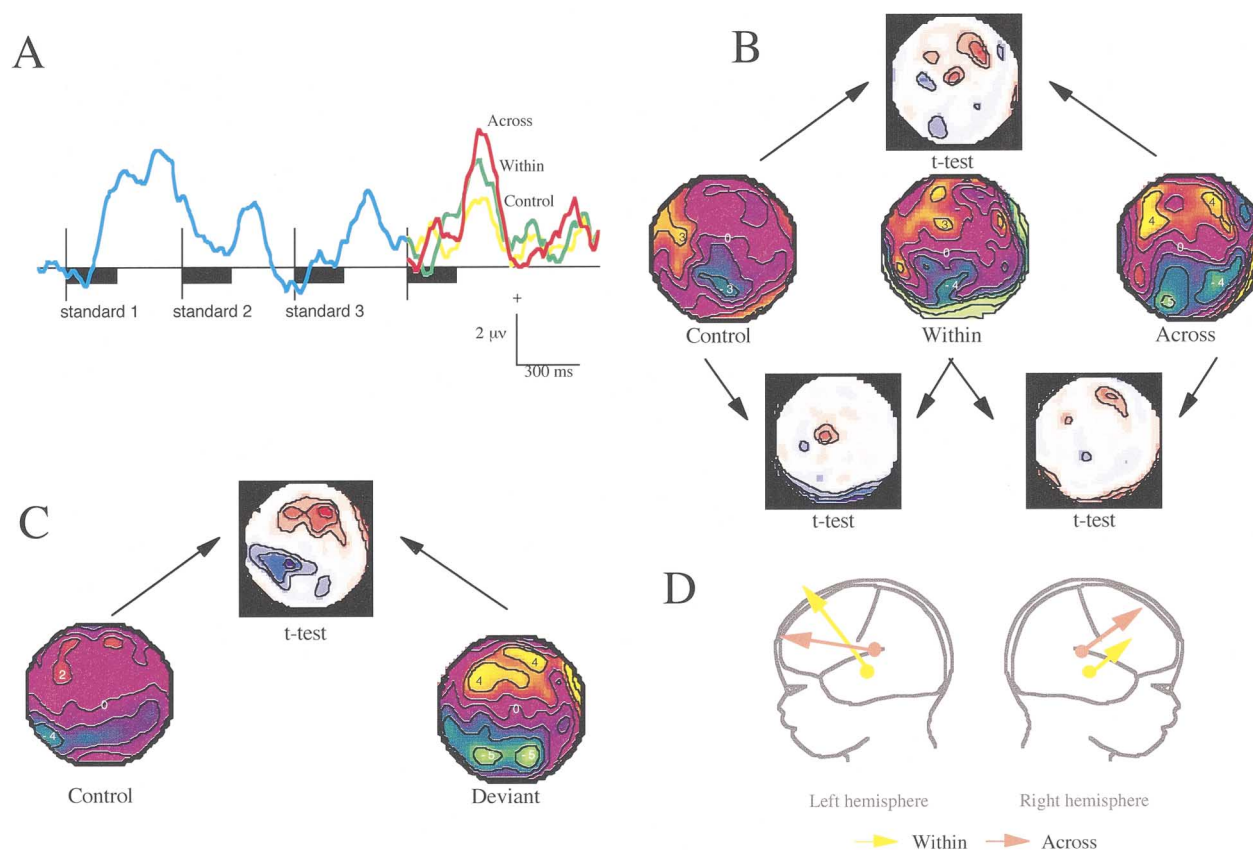
FIG. 1. Infants' evoked responses to syllable change reflect both auditory and phonetic processes of mismatch detection. (**A**) Grand-averaged response recorded from a left frontal electrode, showing a decrease to repetition and a recovery following syllable change. (**B,C**) Topography of evoked responses and maps of statistical significance (*t*-test) at 454 ms following syllable onset, where the maximal response to novelty was observed. For comparison purposes, (C) shows the responses of infants to a change in natural syllables, as previously reported.[6] (**D**) Dipole model for peak 2 in WC and AC conditions.

phonological mismatch process. None of these effects interacted with hemisphere. At the occipital site, the only significant effect was a significant difference between AC and CO ($F(1,23) = 5.6$, $p = 0.027$).

A dipole modelling was computed with the BESA software (Neuroscan Inc.) with a three-layer spherical head model based on the average 4-month-old head radius, skull and scalp thickness (respectively 65, 4 and 3 mm) on a 80 ms time window length around the maximum of peak 2 (359–442 ms). The two dipoles of the source model were constrained to remain symmetric in location in the left and right hemisphere, while their orientations were left unconstrained. For both deviant conditions, WC and AC, dipoles were found to be located in the temporal lobes, with a greater left than right dipole amplitude. A high percentage of the voltage variance was explained by the model (88.9% in AC and 83.4% in WC). A large part of the residual variance (RV) rate may be explained by the systematic bias introduced by the simplified spherical geometry, together with the probable lower signal to noise ratio in EEG

infants' data compared with that from adults. In this spherical model, dipoles were located 7 mm more posterior and 11 mm more dorsal in AC than in WC (Fig. 1D).

Discussion

Although it has been shown since the early 1970s that infants perceive phonemes categorically, the neural bases of this capacity have not been described. Dehaene-Lambertz and Dehaene[6] have shown that a discrimination response to a new syllable occurs after about 400 ms. Here, we demonstrated that this response is sensitive to phonetic information, similar acoustical changes generating distinct activation patterns depending on their linguistic relevance (Fig. 1).

The fact that a significant voltage difference between acoustical and phonological processing was observed over frontal electrodes does not necessarily imply that phoneme perception involves frontal areas. In adults, although auditory mismatch detection

induces a predominantly right frontal negativity, its main generators are probably located inside the temporal lobes.[4] In the present work with infants, the topography of peak 2, in all conditions, was consistent with generators in the left and right temporal cortices. A dipole modelling algorithm suggested that the generator of peak 2 are more posterior and dorsal in case of phonetic deviance (AC trials) than in case of acoustical deviance (WC trials). It is presumably this topography difference in temporal activity that was responsible for the observed voltage difference over frontal electrodes, rather than a putative contribution of frontal areas to phonological processing.

We should mention that although there was always a tendency of greater voltage amplitude above the left than the right hemisphere, an hemisphere effect was found only for peak 2 across the first three syllables of trials. In particular, there was no significant hemispheric asymmetry in the discrimination response. Näätänen et al.[4] showed with magnetoencephalography that, in adults, a phonetic change induces a larger hemispheric asymmetry than a non-phonetic change. Our results suggest that in infants, although the left hemisphere is more active during syllable comprehension, syllable discrimination itself may engage more bilateral processing. This conclusion must remain very tentative however, because it is based on accepting the null hypothesis. Only the comparison between linguistic and non linguistic stimuli could definitively conclude about the existence of an early left specialisation for linguistic processes.

Conclusion

We have demonstrated that, in infants as in adults, auditory mismatch detection is not a single homogeneous process, but involves neuronal networks depending on the deviant parameter. Furthermore infants, as adults, already possess a neuronal network dedicated to phonological processing, above and beyond acoustical processing. The present work, while showing that some phoneme boundaries are already encoded in the infant brain by three months of age, does not address the issue of how and when exposure to maternal language alters this early linguistic competence. This might be studied, in the future work, by contrasting evoked responses to native and non-native phoneme boundaries and following their evolution across the first year of life.

References

1. Werker JF and Tees RC. JASA **75**, 1866–1878 (1984).
2. Miyawaki K, Strange W, Verbrugge R et al. Percept Psychophys **18**, 331–340 (1975).
3. Dehaene-Lambertz G. NeuroReport **8**, 919–924 (1997).
4. Näätänen R, Lehtokovski A, Lennes M et al. Nature **385**, 432–434 (1997).
5. Eimas PD, Siqueland ER, Jusczyk PW et al. Science **171**, 303–306 (1971).
6. Dehaene-Lambertz G and Dehaene S. Nature **370**, 292–295 (1994).
7. Christophe A and Moron J. Nature **370**, 250–251 (1994).
8. Werker JF and Lalonde CE. Dev Psy **24**, 672–683 (1988).
9. Perrin F, Pernier J, Bertrand D et al. Electroencephalogr Clin Neurophysiol **72**, 184–187 (1989).