Development of language-specific phoneme representations in the infant brain

Marie Cheour[1], Rita Ceponiene[1], Anne Lehtokoski[1], Aavo Luuk[2], Jüri Allik[2], Kimmo Alho[1,3] and Risto Näätänen[1,3]

[1] *Cognitive Brain Research Unit, Department of Psychology, University of Helsinki, FIN-00014, Finland*

[2] *Department of Psychology, University of Tartu, Estonia*

[3] *BioMag laboratory, P.O.Box 508 00029 HYKS, Finland*

Correspondence should be addressed to M.C. (Marie.Cheour@Helsinki.fi)

Studies using behavioral methods, such as head-turning experiments, in which children are conditioned to turn their heads toward the sound source when they detect a change in the sound, have shown that environment has an important effect on how infants perceive language[1–4]. Young infants are able to discriminate almost all phonetic contrasts, whereas older infants discriminate better between phonemes that occur in the language that they normally hear, rather than foreign-language phonemes. Here we demonstrate the development of language-specific 'memory traces' in the brains of the same group of infants between six months and one year of age.

The Estonian and Finnish languages, which are closely related to each other, have very similar vowel structures[5]. For example, the vowels /e/ and /ö/, which differ only in the second-formant (F2) frequency, exist in both languages. However, only Estonian has the vowel /õ/, which is approximately between /ö/ and /o/ (Fig. 1). We used these phonemes to investigate the development of language-specific memory traces in infants. This was done by analyzing mismatch negativity (MMN), an electric brain response automatically elicited by infrequent changes (deviant stimulus) in a repetitive (standard) stimulus[6–12]. The MMN amplitude increases with an increasing acoustic difference between deviant and standard stimuli[9]. Thus, when the phoneme /e/ is the standard, the MMN amplitude should be larger when the deviant stimulus

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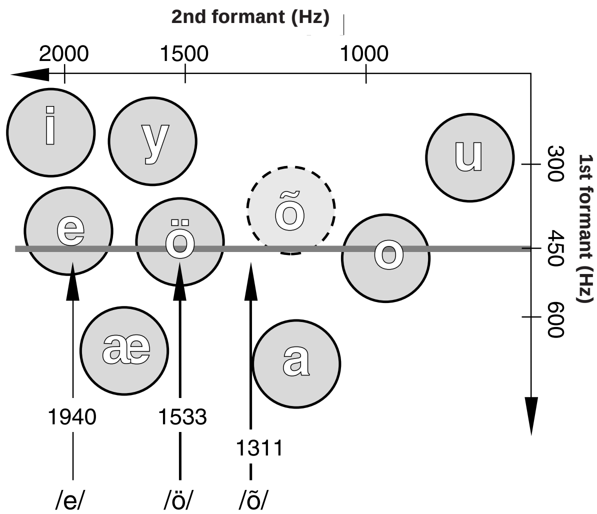

Fig. 1. Stimuli used in the experiment. Vowels of 75 dB SPL, lasting 400 ms (with 10 ms rise and fall times), were presented through two loudspeakers about 50 cm from the infants' ears. The (onset-to-onset) interstimulus interval was 1100 ms. The upward arrows show the locations of the vowel stimuli in F1–F2 space. The standard stimulus was the Finnish and Estonian vowel /e/. The deviant stimulus /ö/ was a vowel shared by both languages; the deviant stimulus /õ/ is a vowel only in Estonian. The F2 frequency chosen for the frequent stimulus produced the best model of the /e/ prototype of the Finnish and Estonian languages as judged by adult listeners[6]. For /e/ it was 1940 Hz; for /ö/, 1533 Hz; and for /õ/, 1311 Hz. The first (F1), third (F3), and fourth (F4) formants for each vowel were constant at 450, 2540, and 3500 Hz, respectively. The average fundamental frequency (F0) was 105 Hz. The vowels were generated by the production of synthetic stimuli from natural glotted excitation in conjunction with a vocal-tract model[6].

is /õ/ than when it is /ö/. Nevertheless, the MMN amplitude in Finnish adults[6] was smaller for /õ/ than /ö/, possibly because /õ/ is not a vowel in Finnish. Consistent with this, the MMN attenuation for /õ/ relative to /ö/ did not occur in Estonian adults, in whose language /õ/ is a vowel. Perhaps as /õ/ does not exist in Finnish, Finns usually have very little experience with it, and therefore a memory trace for it has not been developed in their brain.

We recorded the brain responses of nine Finnish (seven male and two female) and nine Estonian (six male and three female) healthy infants without hearing deficits, all from monolingual families, while the infants sat on a safety seat. To distract the children from the stimuli and to minimize eye and body movements, an assistant entertained them with silent toys during the experiment. The Finnish infants were studied at six months of age (average, six months one day; range, six months ± ten days) and again at one year of age (average, one year three days; range, one year ± fourteen days). The Estonian infants were studied when they were one year old (average, one year eight days; range, one year ± fourteen days). Parents gave informed consent for their child's participation. The /e/ phoneme was the standard stimulus, and it was randomly replaced by deviant /õ/ or /ö/[5] (Fig. 1), with a probability of occurrence of 0.1 for each.

Electroencephalograms (EEGs), amplified by SynAmps at DC-100 Hz and digitized at 250 Hz, were recorded at frontal (Fz) and central (Cz) electrodes. Eye movements were monitored with electro-oculogram (EOG) electrodes attached below and at the lateral corner of the left eye. All electrodes were referred to a left-mastoid electrode. EEG epochs with EEG or EOG artifacts exceeding 250 μV at any electrode were discarded, as were epochs for the first two stimuli of each block. For each infant, there were at least 90 acceptable EEG epochs for each deviant stimulus. Frequencies higher than 15 Hz or lower than 0.1 Hz were digitally filtered out off-line. A baseline of 0 μV was set at the mean amplitude over the 50-millisecond pre-stimulus period. The MMN amplitude was measured from the difference waves (obtained by subtracting the average standard-stimulus response from the average deviant-stimulus response) separately for each subject and electrode, as the mean amplitude, relative to the baseline, of the 80-ms period centered on the largest peak between 250–450 ms. The differences in the MMN amplitude in response to the deviant /ö/ and /õ/ stimuli were tested with three-way ANOVA analysis: group (Estonian, Finnish one-year-old, Finnish six-month-old) × stimulus type (/õ/, /ö/) × electrode (Fz, Cz).

Considerable MMN responses were elicited by both deviant stimuli in all groups (Figs 2 and 3). In six-month-old Finnish infants, the MMN amplitude was larger, although not significantly, for /õ/ than for /ö/, that is, larger for the acoustically more different stimulus. Thus, these six-month-old infants perceived the differences between these stimuli mainly or only acoustically. In contrast, at one year of age, the same Finnish infants had a much smaller MMN amplitude for the Estonian vowel /õ/ than for the Finnish vowel /ö/, although the acoustical difference from /e/ was larger to /õ/ than to /ö/. A three-way ANOVA showed a highly significant group (six- versus twelve-month-old Finns) × stimulus type (/õ/ versus /ö/)

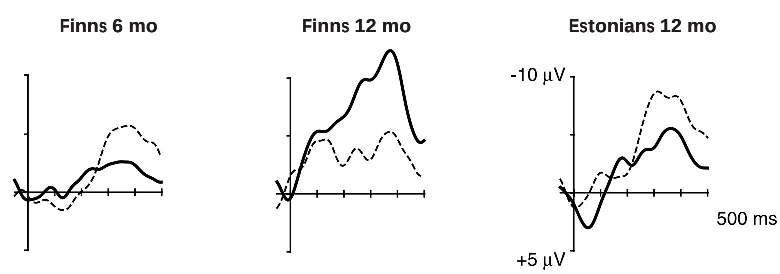

Fig. 2. The MMN amplitude at the central Cz electrode (grand-average, deviant-standard difference waveform, averaged across nine infants) reflects the development of language-specific memory traces in Finnish infants. At six months of age, their MMN amplitude reflects only the acoustical difference between the deviant and standard stimuli. In contrast, at one year of age, the MMN amplitude in the same children was considerably enhanced for the Finnish vowel /ö/ and considerably attenuated for the Estonian vowel /õ/. In Estonian one-year-old infants, the MMN amplitude reflected only the acoustic difference between deviant and standard stimuli, as both deviant stimuli are vowels in Estonian. —— standard /e/ - deviant /ö/, a vowel shared by Finnish and Estonian languages, - - - standard /e/ - deviant /õ/, an Estonian vowel.

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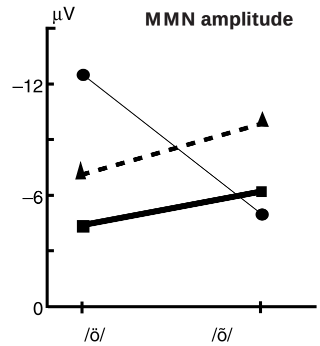

Fig. 3. The MMN peak amplitude (at Cz) as a function of the deviant stimulus. Results are shown for three groups: six-month-old (squares, thick solid line) and one-year-old (circles, thin solid line) Finnish infants and one-year-old Estonian (triangles, dotted line) infants. These are arranged in the order of increasing F2 difference from the standard stimulus. **–■,** 6-month-old Finns; –●, one-year-old Finns; --▲, one-year-old Estonians.

interaction ($F(1,16) = 16.23$; $p < 0.001$). The least significant difference post-hoc test showed that the MMN amplitude for the Finnish vowel /ö/ was increased ($p < 0.01$) and for the Estonian vowel /õ/ was decreased ($p < 0.02$) for Finnish infants between six and twelve months of age. Therefore, it seems that the memory trace for the native vowel /ö/ was formed before the age of one year in these Finnish children.

According to these results, the MMN amplitude for /õ/ should not be smaller than that for /ö/ in Estonian one-year-old infants, as both are vowels in Estonian. Indeed, there was no distinct difference in the MMN amplitude between these two vowels; if anything, the MMN amplitude for /õ/ was larger than that for /ö/, apparently because of the greater acoustical difference from /õ/ to /e/ than from /ö/ to /e/. Moreover, a comparison of one-year-old Finnish and Estonian infants yielded a highly significant group × stimulus type interaction ($F(1,16) = 14.88$; $p < 0.002$). The least significant difference post-hoc test showed that this resulted from the MMN amplitude for /ö/ being larger than that for /õ/ in the one-year-old Finnish infants ($p < 0.002$). Furthermore, the MMN amplitude for the Estonian vowel /õ/ was significantly larger in the Estonian than in the Finnish one-year-old infants ($p < 0.004$).

Our data indicate that language-dependent memory traces in the human brain emerge before the age of 12 months. To our knowledge, this is the first definite neurophysiological evidence for the development of brain memory traces for speech sounds in infants. Our results show that by the age of one year, the MMN amplitude increases for native phonemes and decreases for non-native phonemes. Thus, during their cognitive development, the ability of infants to discriminate native speech sounds improves, while at the same time they seem to lose some of their ability to discriminate non-native speech sounds[1–4,13–15].

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