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Report

Brain Responses in 4-Month-Old Infants Are Already Language Specific

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Summary

Language is the most important faculty that distinguishes humans from other animals. Infants learn their native language fast and effortlessly during the first years of life, as a function of the linguistic input in their environment. Behavioral studies reported the discrimination of melodic contours [1] and stress patterns [2, 3] in 1–4-month-olds. Behavioral [4, 5] and brain measures [6–8] have shown language-independent discrimination of phonetic contrasts at that age. Language-specific discrimination, however, has been reported for phonetic contrasts only for 6–12-month-olds [9–12]. Here we demonstrate language-specific discrimination of stress patterns in 4-month-old German and French infants by using electrophysiological brain measures. We compare the processing of disyllabic words differing in their rhythmic structure, mimicking German words being stressed on the first syllable, e.g., *pápa/daddy* [13], and French ones being stressed on the second syllable, e.g., *papá/daddy*. Event-related brain potentials reveal that experience with German and French differentially affects the brain responses of 4-month-old infants, with each language group displaying a processing advantage for the rhythmic structure typical in its native language. These data indicate language-specific neural representations of word forms in the infant brain as early as 4 months of age.

Results

A group of 50 healthy native German infants and a group of 50 healthy native French infants were tested at the age of 4–5 months (mean 4 months and 2 weeks). A standard oddball mismatch paradigm was used to test for stress-pattern discrimination. In this paradigm, participants listen to a series of stimuli consisting of one stimulus type, the "standard," which is repeated frequently, and another infrequently occurring stimulus, the "deviant," interspersed [14].

The stimuli used consisted of the pseudoword *baba*, either stressed on the first syllable (*bába*) or stressed on the second syllable (*babá*). Because stress is dominantly marked by syllable length, this resulted in two stimuli, one with the first syllable being long and the second being short (ba:ba) and one with the first syllable being short and the second being long (baba:) (see Figure 1). In order to compare the infants' event-related potential (ERP) to acoustically identical stimuli, we presented and analyzed each stimulus as a standard and as a deviant. This was possible because of a crossed design with two runs, one in which /ba:ba/ served as the standard and /baba:/ as the deviant and one in which /baba:/ was the standard and /ba:ba/ the deviant.

The averaged ERPs showed a different pattern for the German and the French groups (see Figure 2). German infants demonstrated a clear positive mismatch response (MMR) when the deviant stimulus had the stress on the second syllable, but no MMR when the stress was on the first syllable. For French infants, we observed the reverse pattern, with a clear positive MMR when the stress was on the first syllable, but no MMR when the stress was on the second syllable. Thus both groups reacted strongly to the stress pattern that was deviant to that of their native language. This observation was statistically confirmed.

Because the time windows were necessarily different for the items with stress on the first versus second syllable, separate analyses of variance (ANOVAs) were performed for each item type. An analysis for the time window between 450 and 650 ms with the factors condition by hemisphere by region by language by age for items with stress on the first syllable revealed a main effect of condition [$F(1,96) = 16.385$, $p < 0.0005$] and a condition-by-language interaction [$F(1,96) = 7.014$, $p < 0.009$]. Separate analyses for each group showed no condition effect for German infants, but a significant condition effect [$F(1,49) = 30.167$, $p < 0.0001$] for French infants. The comparable analysis for items with stress on the second syllable for the time window 650–850 ms revealed a condition effect [$F(1,96) = 4.324$, $p < 0.040$], a condition-by-region interaction [$F(1,96) = 11.836$, $p < 0.001$], and a condition-by-language interaction [$F(1,96) = 4.967$, $p < 0.028$]. French infants showed no condition effect, but for German infants a significant condition effect [$F(1,49) = 11.876$, $p < 0.001$] and an interaction of condition with region [$F(1,49) = 6.413$, $p < 0.015$] were present. This interaction was caused by greater responses over the frontal than the central region [$T(49) = 2.532$, $p < 0.015$], but analyses of single regions revealed significant condition effects over both regions [frontal: $T(49) = 3.737$, $p < 0.0005$; central: $T(49) = 3.028$, $p < 0.004$]. Thus, the overall response pattern is similar in the French and German infant groups.

Although there was no interaction of condition with hemisphere, we found hemisphere main effects for

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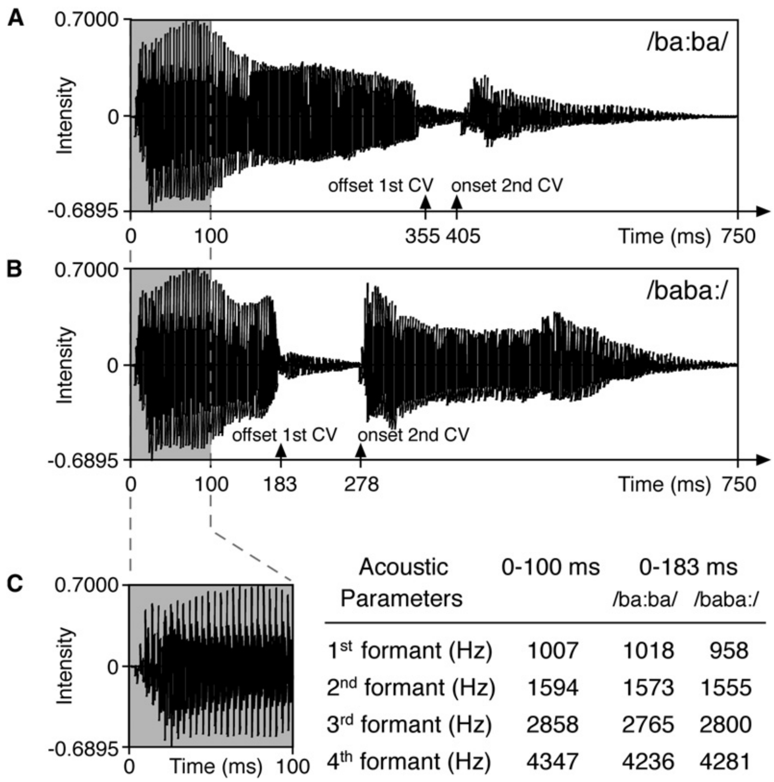

Acoustic Parameters	0-100 ms	0-183 ms /ba:ba/	0-183 ms /baba:/
1st formant (Hz)	1007	1018	958
2nd formant (Hz)	1594	1573	1555
3rd formant (Hz)	2858	2765	2800
4th formant (Hz)	4347	4236	4281

Figure 1. Illustration of Acoustic Parameters of the Pseudoword Stimuli

Displayed is the intensity normalized to maximum intensity (0.7 × I/Imax). Maximum intensity is equal for both stimuli. Two disyllabic pseudowords differing in stress pattern were used. They were produced in infant-directed speech by a young mother who is a native speaker of German. We replaced the first 100 ms of the stimulus with stress on the first syllable with the first 100 ms of the stimulus with stress on the second syllable in order to control for the onset of the acoustic differences present in natural speech. Thus, the first 100 ms of both stimuli were identical. This was done after recording and digitization (44.1 kHz, 16 bit sampling rate). A description of the acoustic parameters of these first 100 ms is given in (C). (A) represents the stimulus with stress on the first syllable /ba:ba/. The offset first syllable was 355 ms, the onset second syllable was 405 ms, and the total duration was 750 ms. (B) represents the stimulus with stress on the second syllable /baba:/. The offset first syllable was 183 ms, the onset second syllable was 278 ms, and the total duration was 750 ms. Because the pitch values for the first vowel were very similar for both stimuli, no pitch discontinuity was present despite cross-splicing. Both stimuli were judged to sound like natural sounds by three independent German monolingual adults.

both stimulus types in the first time window between 450 and 650 ms (first-syllable-stressed stimulus: $F(2,192) = 6.549$, $p < 0.002$; second-syllable-stressed stimulus: $F(2,192) = 13{,}759$, $p < 0.0001$) and a tendency for this effect in the second time window between 650 and 850 ms (first-syllable-stressed stimulus: $F(2,192) = 2.272$, $p < 0.106$; second-syllable-stressed stimulus: $F(2,192) = 2.857$, $p < 0.065$). In the left hemisphere, higher amplitudes were observed than in the right hemisphere in both the first time window (first-syllable-stressed stimulus: $T(99) = 3.223$, $p < 0.002$; second-syllable-stressed stimulus: $T(99) = 3.857$, $p < 0.0002$) and the second time window (first-syllable-stressed stimulus: $T(99) = 1.999$, $p < 0.048$.; second-syllable-stressed stimulus: $T(99) = 1.995$, $p < 0.049$).

Discussion

In the present ERP data, we found differences in hemispheric activations with a stronger left than right hemispheric involvement in processing word-like stimuli. This is in line with results from earlier imaging work [15, 16] suggesting a dominance of the left hemisphere for natural speech in early infancy.

More strikingly, however, the present data demonstrate brain responses of 4-month-old infants to be specific to a particular language. German infants displayed a mismatch response (MMR) to stimuli with stress on the second syllable and French infants a MMR to stimuli with stress on the first syllable, with each group showing a MMR to the stimulus that is deviant relative to the dominant stress pattern in its native language.

Within the ERP literature, a positive MMR has been interpreted as a discrimination response specific to infants. In adults, the deviant stimulus compared to the standard leads to a negativity around 120 ms after stimulus onset. In infants, the electrophysiological response observed is sometimes a negativity or a positivity, depending on the developmental state of infants and the difficulty of the discrimination task [17, 18]. Both responses are viewed as a mismatch response indicating the use of different memory structures for processing the standard and the deviant stimulus. Recently the idea was promoted that the negativity may represent a more mature MMR than the positivity, with the positivity reflecting an acoustic form of analysis [12, 18]. It has moreover been proposed that the positivity arises when a special effort is needed to perceptually process the rarely presented deviant stimulus [19]. The present positive MMR observed to the nonnative rhythmic stress pattern is therefore taken to reflect additional effort in the perceptual processing of a stimulus that is not only deviant in the experimental setting but moreover in the respective group's native language. The enhanced effort for the nonnative language deviant indicates that the memory structures for this stress pattern are less well established than those for the native-language stress pattern.

The differential brain-activation patterns observed within language groups for the different stimuli suggest language-specific memory representations for native and nonnative language stimuli. By using an electrophysiological paradigm that in contrast to behavioral measures does not require the infants' attention and their overt responses, we were able to demonstrate

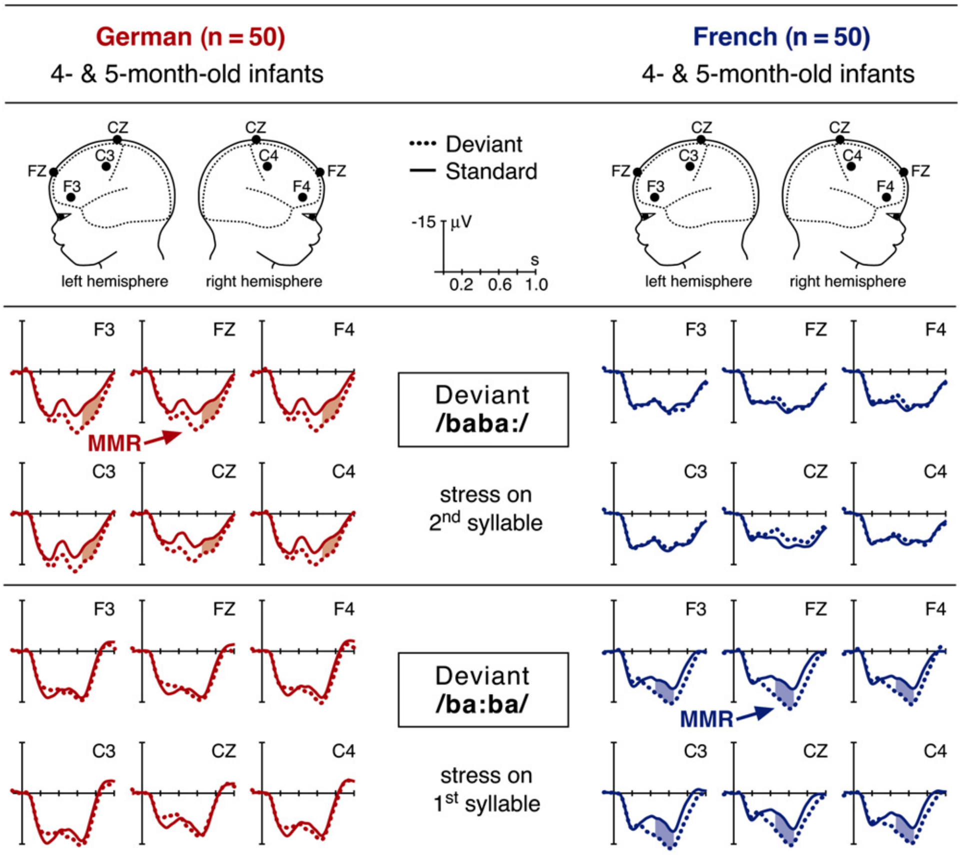

Figure 2. Language-Specific Brain Responses in German and French Infants

Averaged ERPs per condition (solid line represents standard; dotted line represents deviant) for each language group (left panel shows German; right panel shows French) and item type: for items with stress on the second syllable (top panel) and items with stress on the first syllable (bottom panel). Positivity is plotted down. The shaded area indicates the time windows chosen for statistic analysis in which the effect was statistically significant.

that perceptual language skills are tuned to the native language earlier than previously thought. Whereas behavioral studies suggested that such tuning takes place toward the end of the first year of life, the strikingly different brain-activation patterns between German and French infants indicate that language experience affects the infants' neural representation of a word's stress pattern as early as 4 months of age.

Experimental Procedures

Participants and Experimental Design

German infants (28 females, 22 males) had a mean gestational age of 18 weeks and 4 days (ranging from 15 weeks and 4 days to 20 weeks and 5 days). French infants (28 females, 22 males) had a mean gestational age of 18 weeks and 3 days (ranging from 13 weeks and 6 days to 22 weeks). Originally, 70 French infants were tested. In ten of the French infants, only one experimental block could be presented; eight infants did not reach the required numbers of accepted trials after artifact rejection, and two infants had very noisy data. German infants were a subgroup of infants (taken from a larger infant group tested as part of the German Language Development Study [GLAD]) and were matched to the French group with respect to age (4 months or 5 months) and gender. They were all full-term healthy babies with no known sensory or other deficits. All infants were born to monolingual German or French families. Participating families followed the respective institutional consent procedures in German or French. The studies were run under the approval of the ethics committee of the Charité Berlin in Germany or the Cochin Hospital in France.

Two types of acoustic stimuli were used: one disyllabic item with stress on the first syllable (ba:ba) and one disyllabic item with stress on the second syllable (baba:). Stress on the first syllable is the dominant stress pattern for disyllabic words in German. In French, disyllabic words carry stress on the second syllable when produced in isolation.

Stimuli were presented in a passive-listening oddball paradigm (occurrence of standard stimulus: 83%; of deviant stimulus: 17%). To allow the comparison of the identical stimulus as a standard and a deviant, we applied a crossed design: In one experimental block, the stimulus with stress on the first syllable was presented as the deviant and the stimulus with stress on the second syllable as the standard, and in the second experimental block, the former served as the standard and the latter as the deviant (the order of presentation of blocks was counterbalanced across participants). Stimuli were presented via loudspeaker with an intensity of 64 dB sound-pressure level (SPL) in a sound-attenuated booth. Each experimental block consisted of 600 trials with a fixed interstimulus interval of 855 ms. Each block lasted about 12 min. The entire experiment, including preparation and pauses, lasted about 1.5 hr. During the recordings, on occasion infants were entertained by a puppeteer.

ERP Data Acquisition

The electroencephalograph (EEG) was recorded with Ag/AgCL electrodes attached to frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) scalp sites according to the International 10-20 Electrode System. An electrode cap was used. Vertical electro-oculograms (EOGs) were recorded from infra- and supraorbital electrodes located at the right eye, and horizontal electro-oculograms were recorded from lateral electrodes located at both eyes. The recordings were referenced to Cz (because this is a relatively artifact-free electrode in infants) and referenced later to the average of both actively recorded mastoids. Impedances were below 10 kΩ. The EEG and EOG channels were amplified with a PORTI-32/MREFA amplifier (Twente Medical Systems, with input impedance of 10^{12} Ω and analog first-order low-pass filter of 5 kHz), digitized online at a rate of 250 Hz (analog to digital [AD] converter with 22 bit), and stored on hard disk.

A digital band-pass filter ranging from 0.3 to 15 Hz (−3 dB cut-off frequencies of 0.37 and 14.93 Hz) was applied to remove slow drifts and muscle artifacts while preserving most of the original signal. Trials exceeding a standard deviation of 100 μV within a sliding window of 500 ms were rejected automatically. In the analyses presented here we included only those children who met the criteria of 40 trials per condition. The mean number of accepted deviants was 85 (standard deviation [SD] = 11), and the mean number of accepted standards was 425 (SD = 58). Epochs of 1200 ms from stimulus onset were averaged separately for each condition, electrode, and participant according to a baseline of 200 ms covering 100 ms of the prestimulus and 100 ms of the poststimulus period.

ERP Data Analysis

Statistical analysis was carried out in the following way: For the first-syllable-stressed stimulus, for which a positive peak in the difference wave between deviant and standard was present around 550 ms, mean amplitudes from 450 to 650 ms were analyzed. For the second-syllable-stressed stimulus with a positive peak around 750 ms, mean amplitudes from 650 to 850 ms were analyzed. Three-way ANOVAs with condition (standard versus deviant), hemisphere (left, midline, right), and region (frontal versus central) as within-subject factors, and language group (German versus French) and age group (4 months versus 5 months) as between-subject factors, were conducted for first- and second-syllable-stressed stimuli separately. In this initial analysis conducted with the factor age, no significant condition by age interactions were observed. Therefore, data were pooled over the two age groups when language groups were investigated separately by three-way ANOVAs with condition, hemisphere, and region. Within groups, significant interactions including the factor condition were further analyzed by t tests for each sample. In all ANOVAs, the Greenhouse-Geisser correction was applied whenever there was more than one degree of freedom in the numerator.

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