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Research report

Discrimination of word stress in early infant perception: electrophysiological evidence

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Abstract

Language acquisition crucially depends on the ability of the child to segment the incoming speech stream. Behavioral evidence supports the hypothesis that infants are sensitive to the rhythmic properties of the language input. We recorded event-related potentials (ERPs) to varying stress patterns of two syllable items in adults as well as in 4- and 5-month-old infants using a mismatch negativity (MMN) paradigm. Adult controls displayed a typical MMN to the trochaic item (stress on the first syllable) as well as to the iambic (stress on the second syllable) item. At the age of 4 months, no reliable discrimination response was seen. However, at the age of 5 months, a significant mismatch response (MMR) was observed for the trochaic item, indicating that the trochee, i.e. the most common stress pattern in German, was separated consistently from the iambic item. Hence, the present data demonstrate a clear development between 4 and 5 months with respect to the processing of different stress patterns relevant for word recognition. Moreover, possible contributions of different filter settings to the morphology of the mismatch response in infants are discussed.
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Theme: Neural basis of behavior
Topic: Cognition

Keywords: Infant; Event-related potential (ERP); Language acquisition; Mismatch negativity (MMN); Prosody

1. Introduction

One of the crucial problems for the language learning child is how to segment the incoming speech stream. The influential ‘‘prosodic bootstrapping’’ account holds that prosodic information, such as intonational phrase boundaries and syllable stress, is used to guide early segmentation processes [27,50]. In stress-timed languages like English or German, the stress pattern of two syllable content words is a very regular prosodic feature: about 90% of these words have stress on the first syllable, indicating a strong/weak or trochaic stress pattern [11,51]. Cutler and colleagues [9,12] suggested that this characteristic rhythmic structure of English could form the basis of an effective segmentation procedure due to the systematic relationship between rhythmic patterns and word boundary location in English: a strong syllable in spontaneous English conversation is very likely to be the onset of a new lexical word. Given its rhythmic organization, the same also holds for German. Word segmentation strategies based on the native-language prosodic pattern of two syllable content words have been proposed for infants as well [10,16,27,29]. Within the prosodic bootstrapping account, it is assumed that infants acquire considerable information about possible word boundaries in their native language through different types of perceptual cues provided by the speech signal. In fact, it was demonstrated that infants’ sensitivity to native-language sound structure increases between 6 and 9 months of age (for a review, see Ref. [27]). While English learning infants at the age of 9 months listened significantly longer to two syllable words with a trochaic than with an iambic stress pattern, 6 months old English-learners did not [29]. In addition, 9 months old English-learners were able to segment words in an unfamiliar language with the same predominant stress pattern, namely Dutch [24]. More recently, it was shown that 6 months old German infants listened significantly longer to trochaic than to iambic items when presented with two syllable pseudowords varying only

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in stress pattern but not in phonetic content [23]. Moreover, infants at the age of 7.5 months are likely to mis-segment weak/strong, i.e. iambic words at the beginnings of strong syllables (e.g. they segment *prize* rather than *surprise*), indicating that they rely on a metrical segmentation strategy to identify word onsets [30]. The speech signal, however, also provides other word boundary cues, such as the segmental organization of phonemes (phonotactics) [36]. It was demonstrated that 9 months old German infants were sensitive to the phonotactic structure of word boundaries when word-like items were presented in isolation. Furthermore, this sensitivity was even observed when the critical items were presented embedded in two identical context syllables, i.e. when keeping the language processing requirements for the given context low. As no listening preference was found when the speech input was low-pass-filtered, thus eliminating all phonetic cues, the combined data suggest that 9 months old infants' ability to identify word boundaries is indeed based on the processing of phonotactic information [19]. Moreover, the statistical likelihood of one syllable following another (i.e. transitional probabilities) has also proven to be a cue for word segmentation in English infants at the age of 8 months [48]. However, as infants at the age of 7.5 months have been demonstrated to follow a rhythmical segmentation strategy, prosodic stress cues seem to be one of the first sources of information they draw on [28]. The combined data from these behavioral studies indicate a high sensitivity to phonological cues between the age of 6 and 9 months. Yet, behavioral experimental designs rely on attentional and motoric abilities of the child. Neurophysiological measures, in contrast, are able to provide direct evidence for the neurobiological processes underlying speech discrimination abilities independent of other cognitive and motor abilities.

In adults, event-related brain potentials (ERPs) have been applied successfully to study auditory discrimination. Numerous investigations have demonstrated that the adult listener's brain produces a discrimination response as early as 100–200 ms after change onset when a deviant stimulus is presented in a series of standard stimuli (for a recent review, see Ref. [42]). This response is a negative component observable in the difference wave (ERP deviant stimulus minus ERP standard stimulus) named mismatch negativity (MMN) [39]. The MMN is interpreted to reflect the detection of a deviance in the auditory input from information established in sensory memory. This auditory process itself, located in the auditory cortices bilaterally, is assumed to be pre-attentive but to trigger frontal cortex activity (reflected by the frontal MMN subcomponent) in adults [21,44]. MMN has been proposed to be based on the operation of auditory sensory memory [38]. The paradigm has been successfully used to investigate a number of phonemic differences including the perception of durational contrasts in adults and normally developing infants [2,3,13,20] as well as in infants at risk for dyslexia [34,45]. The enlarged amplitude of MMN to language-specific phonemes in adults as well as in infants has been suggested to additionally reflect the existence of long term, language-specific memory traces [5,41]. Most interestingly, some MMN studies in infants reported a discrimination related negativity appearing at about the same latency as the adult mismatch response, i.e. 100–250 ms after change onset [2,3], whereas others reported a discrimination response with a positive polarity at about 300–400 ms after change onset [13–15,20,45]. Candidate hypotheses to account for these results are either based on maturational or on functional arguments. A functional difference between the positivity and the negativity was assumed by some authors, who state that the positive deflection could arise from an obligatory nonrefractory response to a new stimulus or possibly represent a P3a [2,4]. Other authors introduced the view that the genuine MMN could be masked by prepoderant slow wave activity in infants [37]. Alternatively, it was proposed that the positivity could represent a genuine discrimination response related to the immaturity of the infant brain, e.g. with respect to myelination [45]. So far, no satisfactory explanation for this difference in timing and polarity of the mismatch response (MMR) in infants has been provided. A review of the infant MMR studies reported in the literature (Table 1), however, raises the possibility that the difference in the polarity of the MM response is dependent on the filter setting. Table 1 indicates that besides differences in the number of accepted deviant items, one of the most prominent methodological differences between these studies was the different filter settings used.

The present study systematically examined the sensitivity to trochaic and iambic stress patterns in two syllable pseudowords. Syllable stress as a crucial prosodic element of German is marked by increase in duration, loudness and frequency, with duration being the most critical feature [26]. Three groups were examined: German adults, German infants at the age of 4 months and at the age of 5 months. Both items were produced in infant-directed speech (IDS), which is commonly preferred by infants of a few days of age to 9 months [7]. IDS items are usually spoken at a slower rate, at a higher pitch and with a wider frequency range [17,18]. These features of IDS are supposed to promote language learning in infants [31]. The MMN paradigm was used to investigate the ability to discriminate trochaic (stress on the first syllable) from iambic (stress on the second syllable) stress patterns in two CVCV pseudowords and vice versa. In contrast to earlier studies [32,35] on infant processing of two syllable items, the present study only used stimuli of the same total duration to exclude any possible influence of different offset responses on the morphology of the difference wave [32]. Another aim of the study was to explore the possible contributions of different filters to the heterogenity of results, with respect to the polarity of the mismatch response, in infant studies reported in the literature. Therefore, we applied two different filters to the infant data obtained: a highpass 0.3 Hz, preserving most of the original signal; and a bandpass 1–15 Hz filter, where the ratio of the typical MMN frequencies in the theta range was relatively high [1,47]. The presentation

Table 1
Summary of mismatch studies to speech stimuli in infants (0–6 months, not in quiet sleep)

Study	Subjects	Deviant stimulus	Change onset (ms)	ISI (off/on)	Filter	Mismatch polarity	Latency after change onset (ms)
Cheour et al. [3]	3-month-olds $N=6$	vowel difference 1. /i/: 100 ms	0	700 ms	bandpass 0.1–30 Hz	neg	200
Cheour et al. [4]	6-month-olds $N=9$	vowel difference 1. /ö/: 400 ms 2. /õ/: 400 ms	0	700 ms	bandpass 0.1–15 Hz	neg	250–450
Dehaene–Lambertz and Dehaene [15]	2–3-month-olds $N=16$	place of articulation 1. /ba/: 289 ms 2. /ga/: 289 ms	0	SOA 600 ms	bandpass 0.5–20 Hz	pos neg	390 680
Dehaene–Lambertz and Baillet [14]	3-month-olds $N=24$	categorical perception 1. within-category syllable: 275 ms 2. across-category syllable: 275 ms	0	SOA 600 ms	bandpass 0.5–20 Hz	pos	400
Friederici et al. [20]	2-month-olds $N=10$	vowel duration 1. /ba/: 341 ms	30	855 ms	highpass 0.3 Hz	pos neg	370 770
Kushnerenko et al. [32]	Newborns 1. $N=12$ 2. $N=9$ 3. $N=15$	consonant-duration in /asa/ 1. /s/: 240 ms 2. /s/: 80 ms 3. /s/: 80 ms	170	310 ms	bandpass 1–15 Hz	1., 2.: neg 1., 2., 3.: neg	150–200 350–450
Leppänen et al. [35]	6-month-olds 1. $N=12$ 2. $N=27$	consonant-duration in /ata/ 1.95 ms 2.255 ms	167	1: pooled 610ms 450 ms 2: 610 ms	bandpass 0.5–35 Hz	1. neg 2. neg	380 400
Pihko et al. [45]	6-month-olds $N=23$	vowel duration 1. /ka/: 110 ms	110	425 ms	bandpass 0.5–35 Hz	pos pos	160 340

neg = negativity, pos = positivity.

of the results will be structured in the following way: in the first section, results of the experiments with German adults will be presented (Experiment 1). The second section provides the results obtained in infants (Experiments 2 and 3). It is divided into two parts: part one presents ERP results after application of the highpass 0.3 Hz filter, whereas part two gives the ERP results after application of the bandpass 1–15 Hz filter.

2. Experiment 1: adults

2.1. Materials and methods

2.1.1. Participants

Experiment 1 was performed with 19 German adults (10 female). They were between 20 and 30 years old (mean 26.7 years) and reported having normal hearing. They were students of the University of Leipzig and were paid for their participation.

2.2. Stimuli and procedure

Two CVCV pseudowords with different stress patterns were naturally produced in infant directed speech by a young mother who is a native speaker of standard German. She was instructed to stress either the first or the second syllable. After recording and digitalization (44.1 kHz, 16 bit sampling rate) the first 100 ms of the trochaic item (/ba:ba/, offset 1st syllable: 355 ms, onset 2nd syllable: 405 ms, total duration: 750 ms) were replaced by the first 100 ms of the iambic item (/baba:/, offset 1st syllable: 183 ms, onset 2nd syllable: 278 ms, total duration: 750 ms). Hence, the acoustic difference started after 100 ms without any discontinuity (see Fig. 1). Both stimuli were easily discernible and judged to sound like natural sounds by three independent German monolingual adult listeners.

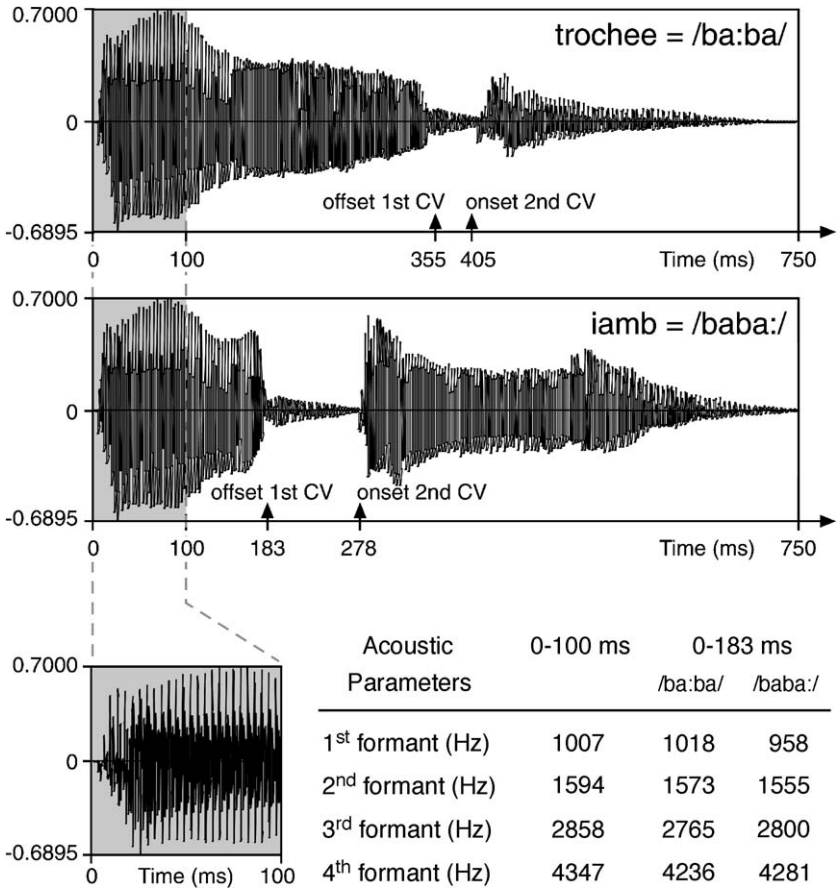
Stimuli were presented in a passive oddball paradigm (standard: $p=5/6$, deviant: $p=1/6$). Two experimental runs were created:

(1) CONDITION TROCHEE: the frequently occurring iambic CVCV item /baba:/ was occasionally replaced by the trochaic deviant CVCV item /ba:ba/ and
(2) CONDITION IAMB: the trochaic CVCV item /ba:ba/ functioned as the standard, whereas the iambic CVCV item /baba:/ took the deviant position.

2.2.1. Control condition: deviant-alone

Deviant-alone conditions are typically conducted to control for the latency and distribution of a true MMN effect. Under such a condition, all deviant stimuli are presented with the same ISI but without any intervening standard [40]. Hence, two additional conditions were created:

(3) DEVIANT-ALONE TROCHEE: the trochaic deviant CVCV item /ba:ba/ was presented without the intervening standard but with the same interstimulus interval;



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

Fig. 1. Illustration of the two stimuli. Physical differences start at 100 ms.

(4) DEVIANT-ALONE IAMB: the deviant iambic CVCV item /baba:/ was presented without the intervening standard but with the same interstimulus interval.

During each experimental run 600 trials were presented with a fixed ISI (offset to onset) of 855 ms. The order of the two runs was counterbalanced across the subjects. Stimuli were presented via loudspeaker with an intensity of 64 dBSPL. All adults read a book during the recordings. Each condition was presented in a separate block. Each block lasted approximately 12 min. The whole experiment, including preparation and pauses, lasted approximately 1.5 h and was completely painless.

2.3. EEG recording

The EEG was registered 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 electrooculograms were recorded from infra- and supraorbital electrodes located at the right eye, horizontal electrooculograms were recorded from lateral electrodes located at both eyes. The recordings were referenced to the left mastoid. The right mastoid was actively recorded. Impedances were below 5 kΩ. The EEG and EOG channels were amplified using a PORTI-32/MREFA amplifier (Twente Medical Systems), digitalized on-line at a rate of 250 Hz, and stored on hard disk. Further analyses were processed off-line. EEG was either bandpass filtered with 1–15 Hz or highpass filtered with 0.3 Hz and algebraically re-referenced to the average of both mastoids.

2.4. Data analysis

Epochs of 1200 ms from stimulus onset were averaged separately for each condition, electrode and participant according to a 200 ms pre-stimulus baseline. Trials exceeding a standard deviation of 80 μV within a sliding window of 200 ms in any channel were rejected automatically. Individual averages included at least 65 accepted deviant items. Statistical analysis for the adult data was carried out for four 20 ms time windows centered around the grand-average MMN peak at Fz, as visual inspection indicated no effect prior to the MMN. In German adults, four-way analyses of variance (ANOVA) for repeated measures were conducted with the factors Discrimination (deviant stimulus vs. standard stimulus), Site (F3/Fz/F4/C3/Cz/C4/P3/Pz/P4), Gender (female vs. male) and Filter (0.3 vs. 1–15 Hz) for each latency window for between-condition-comparisons (i.e.

trochaic deviant item vs. trochaic standard item, iambic deviant item vs. iambic standard item). If significant interactions occurred, separate one-way ANOVAs were conducted. Hemispheric differences were tested with one-way ANOVAs for mean amplitudes of the deviant stimulus. In the deviant-alone control condition, one-way ANOVAs with the factor MMN were conducted for mean amplitudes of the deviant stimuli (deviant-alone trochaic stimulus vs. deviant trochaic stimulus, deviant-alone iambic stimulus vs. deviant iambic stimulus). The Greenhouse–Geisser correction was applied when evaluating effects with more than one degree of freedom in the numerator. The Bonferroni correction was applied when testing consecutive time windows. In the following we report uncorrected degrees of freedom and corrected probabilities.

2.5. Results and discussion

Fig. 2 (left) shows grand-average difference waves, ERP deviant stimulus versus ERP standard stimulus, for the trochaic as well as for the iambic item in adults after application of the 0.3 Hz highpass filter. Fig. 2 (right) displays grand-average difference-waves of the same data after application of the 1–15 Hz filter. For both conditions and filters, a pronounced negativity peaking at about 300 ms, i.e. around 200 ms after change onset, was seen. For the trochaic deviant item, a statistically significant main effect for Discrimination starting at 275 ms until 355 ms was revealed (Table 2a). In addition, significant interactions between Discrimination and Site were seen at 275–315 ms, i.e. also starting at 175 ms after change onset. No significant effects were seen for Gender, Filter or Hemisphere. For the iambic deviant item, a main effect for Discrimination at 275–355 ms was observed. Statistically significant interactions between Discrimination and Site were observed at the same latency. Again, no significant effects for Gender, Filter or Hemisphere were detected (for statistical details, see Tables 2a and b).

Table 2a
Differences between ERP responses to trochaic deviant and trochaic standard in German adults ($N = 19$)

ms	*df*	*t*1	*t*2	*t*3	*t*4
		275–295	295–315	315–335	335–355
TROCHEE					
Discrimination	1.34	13.68***	28.07***	38.70***	33.50***
Site × Discrimination	8.272	5.25**	8.19**		
Discrimination × Gender	1.34				
Gender	1.34				
Filter	1.34				
Discrimination × Filter	1.34				
F3		12.45**	26.51***		
Fz		13.98**	34.41***		
F4		10.86**	31.67***		
C3		16.73***	24.96***		
Cz		18.33***	28.12***		
C4		11.91**	28.61***		
Pz			10.67**		
P4			9.92**		

Time windows (*t*) in ms relative to stimulus onset. Only significant *F*-values are reported.
** $p \leq 0.01$.
*** $p \leq 0.001$.

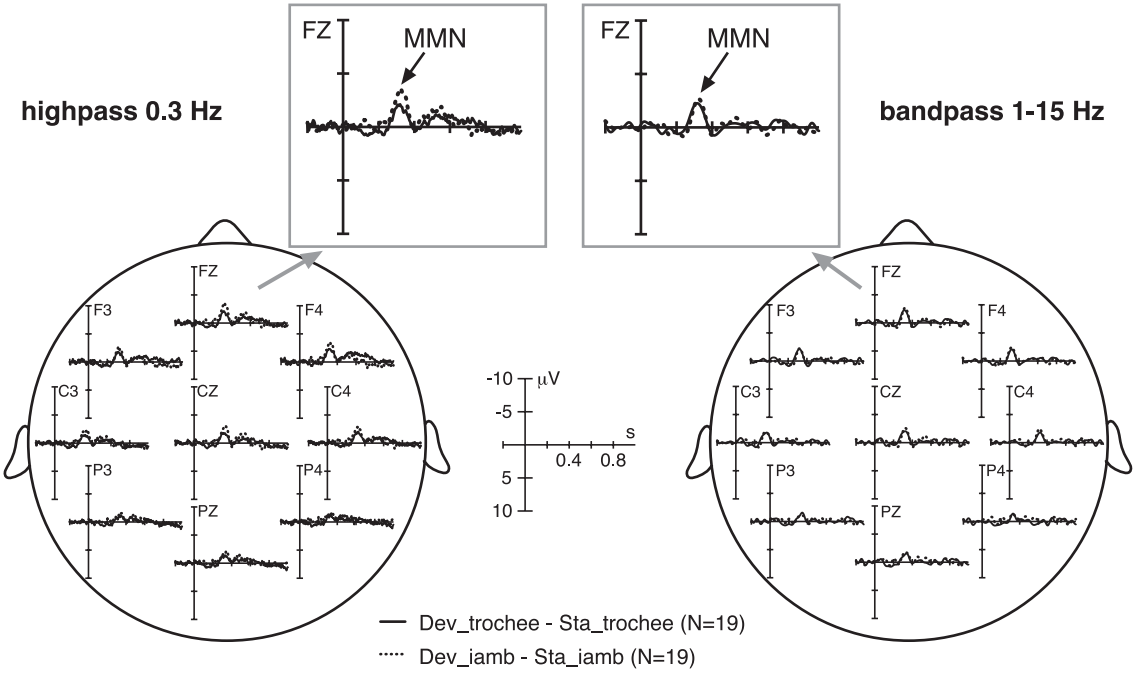


Fig. 2. Grand-average difference waves (deviant minus standard) in adults ($N = 19$). Left: data filtered with 0.3 Hz highpass. Right: data filtered with 1–15 Hz bandpass.

Table 2b
Differences between ERP responses to iambic deviant and iambic standard in German adults ($N=19$)

ms	*df*	*t*1	*t*2	*t*3	*t*4
		275–295	295–315	315–335	335–355
IAMB					
Discrimination	1.34	23.39***	50.71***	52.09***	40.46***
Site × Discrimination	8.272	7.51***	13.54***	15.07***	5.63**
Discrimination × Gender	1.34				
Gender	1.34				
Filter	1.34				
Discrimination × Filter	1.34				
F3		9.94**	29.49***	39.69***	20.91***
Fz		20.18***	47.53***	63.42***	36.64***
F4		29.36***	45.96***	44.20***	29.08***
C3		27.25***	47.92***	47.58***	42.92***
Cz		19.71***	49.12***	62.63***	46.17***
C4		31.63***	63.87***	62.83***	36.16***
P3		8.07**	18.03***	18.05***	28.75***
Pz		14.98***	32.23***	29.89***	35.98***
P4		8.57**	21.66***	24.82***	19.47***

Time windows (*t*) in ms relative to stimulus onset. Only significant *F*-values are reported.
** $p \leq 0.01$.
*** $p \leq 0.001$.

Fig. 3 (left) shows the ERP waveforms for the trochaic stimulus presented in the oddball paradigm, i.e. CONDITION TROCHEE (solid line), as well as the ERP waveform for the trochaic stimulus presented alone, that is at the same ISIs without any intervening standard, i.e. DEVIANT-ALONE TROCHEE (dotted line). As expected, the latter stimulus elicited a higher peak amplitude and had a more central distribution when presented without intervening standard. Statistical analysis revealed a main effect for MMN at 275–315 ms after stimulus onset (Table 3a). Significant interactions MMN × Site were seen at 315–355 ms. Separate one-way ANOVAs indicated that the latter effect was frontally distributed. Hence, the control condition indicated that the negativity elicited by the trochaic deviant item observed at 175–255 ms after change onset can be considered a mismatch negativity with a typical distribution.

Table 3a
Differences between ERP responses to trochaic deviant in the DEVIANT-ALONE CONDITION and trochaic deviant in CONDITION TROCHEE in German adults ($N=18$)

0.3 Hz highpass	*df*	*t*1	*t*2	*t*3	*t*4
ms		275–295	295–315	315–335	335–355
TROCHEE					
MMN	1.17	16.78**	10.51**		
Site × MMN	1.8			9.94***	24.33***
F3				11.81**	28.04***
Fz					17.86**
F4				23.10***	30.95***

Time windows (*t*) in ms relative to stimulus onset. Only significant *F*-values are reported.
** $p \leq 0.01$.
*** $p \leq 0.001$.

Fig. 3 (right) displays the ERP waveforms obtained from the deviant iambic stimulus in CONDITION IAMB (solid line) as well as the ERP waveform resulting from its presentation without intervening standard, i.e. as DEVIANT-ALONE IAMB (dotted line). Again, the typical difference between both conditions was observed. Statistical

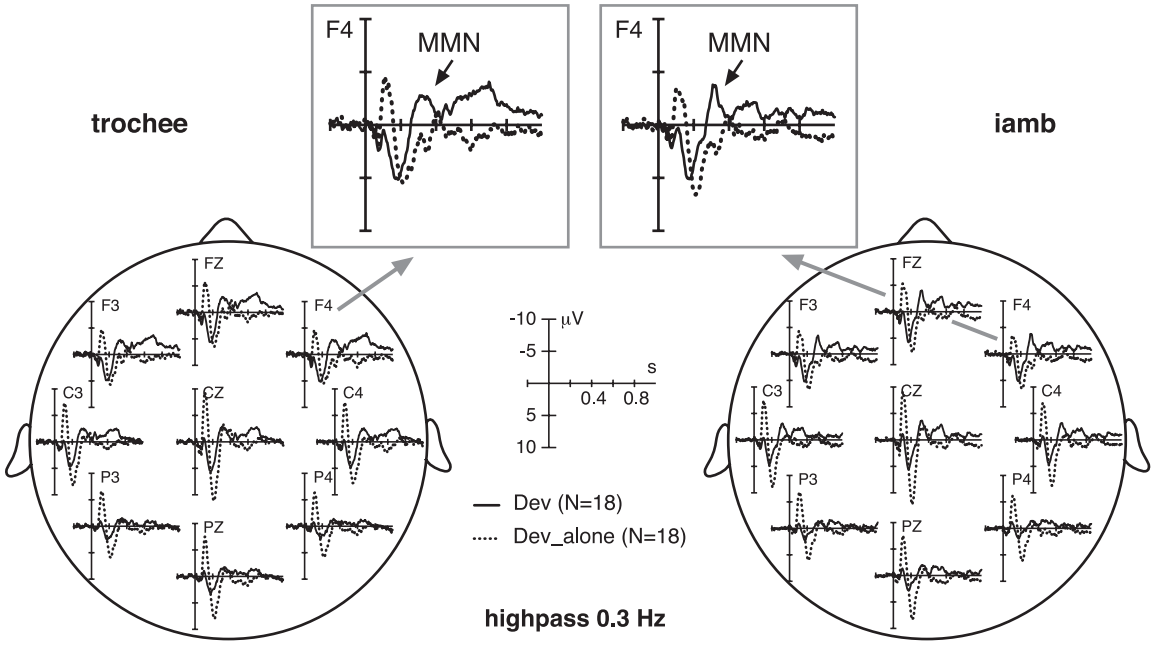


Fig. 3. Left: ERP responses to the trochaic deviant obtained for DEVIANT-ALONE TROCHEE and for CONDITION TROCHEE in adults ($N=18$). Right: ERP responses to the trochaic deviant obtained for DEVIANT-ALONE IAMB and for CONDITION IAMB in adults ($N=18$).

Table 3b
Differences between ERP responses to iambic deviant in the DEVIANT-ALONE CONDITION and iambic deviant in CONDITION IAMB in German adults ($N = 18$)

0.3 Hz highpass	*df*	*t*1	*t*2	*t*3	*t*4
ms		275–295	295–315	315–335	335–355
IAMB					
MMN	1.17	13.30**	9.92**		
Site × MMN	1.8		7.68***	16.71***	8.88***
F3			12.61**	16.13**	
Fz			11.51**	16.91**	
F4			29.92***	27.50***	13.37**
C3			9.04**		
C4			11.90**		

Time windows (*t*) in ms relative to stimulus onset. Only significant *F*-values are reported.
** $p \leq 0.01$.
*** $p \leq 0.001$.

analysis revealed a significant main effect for MMN at 275–315 ms after stimulus onset (Table 3b). Significant interactions MMN x Site were seen at 295–355 ms after stimulus onset for fronto-central sites. Thus, the control condition indicated that the negativity elicited by the iambic deviant stimulus in adults can be interpreted as a mismatch negativity as well.

3. Experiment 2: 4-month-olds

3.1. Materials and methods

3.1.1. Participants

The present experiments are part of the German Language Development Study (GLaD, http://www.glad-study.de) established at the Children's Hospital Lindenhof, Charité, Medical Faculty of the Humboldt University Berlin. Families requested to participate in the study followed institutional informed consent procedures. One aim of the GLaD study is to determine possible processing differences of speech stimuli in infants at risk for Speech and Language Impairment (SLI). Usually, boys are at greater risk to develop SLI than girls [25,49]. With respect to future comparisons between infants at risk and infants not at risk, it is therefore of crucial importance to control for gender effects in both groups. Experiment 2 was conducted with 16-week-olds (0 ± 5 days) who were not at risk for SLI and/or dyslexia. A total of 35 (14 female) full-term infants (GA: 37 to 41 + 6; APGAR 1′>6, APGAR 5′>8, APGAR 10′>9; birth weight females: >2460 g, birth weight males: >2570 g) entered this study. They completed both runs of the experiment and had the required number of accepted deviant items. Eight infants (three female) were excluded from further analysis as they spent most of the experimental time in quiet sleep stage [4,32]. To control for gender effects, the data from an additional five randomly selected boys was not included. Taken together, 22 infants (11 female; mean gestational age: 39.45 weeks, mean conceptual age: 55.41 weeks) participated in Experiment 2. During the recordings they were either awake or in active sleep (three infants were awake throughout the whole experimental time, 19 infants were in mixed states). As no differences in MMR between awake infants and infants in active sleep were found at a SOA of 1.500 ms [6], data were pooled in the present study where SOA was approximately the same. All infants were born to monolingual German families. They passed a peripheral hearing screening with evoked otoacoustic emissions (OAE). None of them had hearing problems (OAE) or a history of neurological or hearing impairment [22,46].

3.2. Stimuli and procedure

Stimuli were the same as in Experiment 1. Due to limitations in infant studies, the deviant-alone control conditions were not performed. Thus, only CONDITION TROCHEE and CONDITION IAMB were performed, i.e. two blocks of approximately 12 min duration each, with occasional breaks whenever necessary. During the recordings, infants were entertained by a puppeteer or by watching a video. Recordings took about 1.5 h including preparation and pauses. They were completely painless.

3.3. EEG recording

EEG recording was the same as in Experiment 1. Impedances were below 10 kΩ.

3.4. Data analysis

Epochs of 1200 ms from stimulus onset were averaged separately for each condition, electrode and participant according to a 200 ms pre-stimulus baseline. Trials exceeding a standard deviation of 80 μV within a sliding window of 200 ms in any channel were rejected automatically. Individual averages included at least 65 accepted deviant stimuli. Statistical analysis was carried out for two 80 ms time windows: one centered around the negative peak at the mismatch latency in adults, i.e. at 275–355 ms after stimulus onset. The second time window was centered around the positive peak of the grand-average difference wave. Three-way analyses of variance (ANOVA) for repeated measures were conducted with the factors Discrimination (deviant stimulus vs. standard stimulus), Site (F3/Fz/F4/C3/Cz/C4/P3/Pz/P4), and Gender (female vs. male) for each latency window for between-condition-comparisons (i.e. trochaic deviant stimulus vs. trochaic standard stimulus, iambic deviant stimulus vs. iambic standard stimulus). If significant interactions occurred, separate one-way ANOVAs were conducted. In order to control for distributional differences, two-way analyses of variance (ANOVA) for repeated measures with the factors Discrimination (standard stimulus vs. deviant stimulus) and Region (anterior: F3, Fz, F4; central:

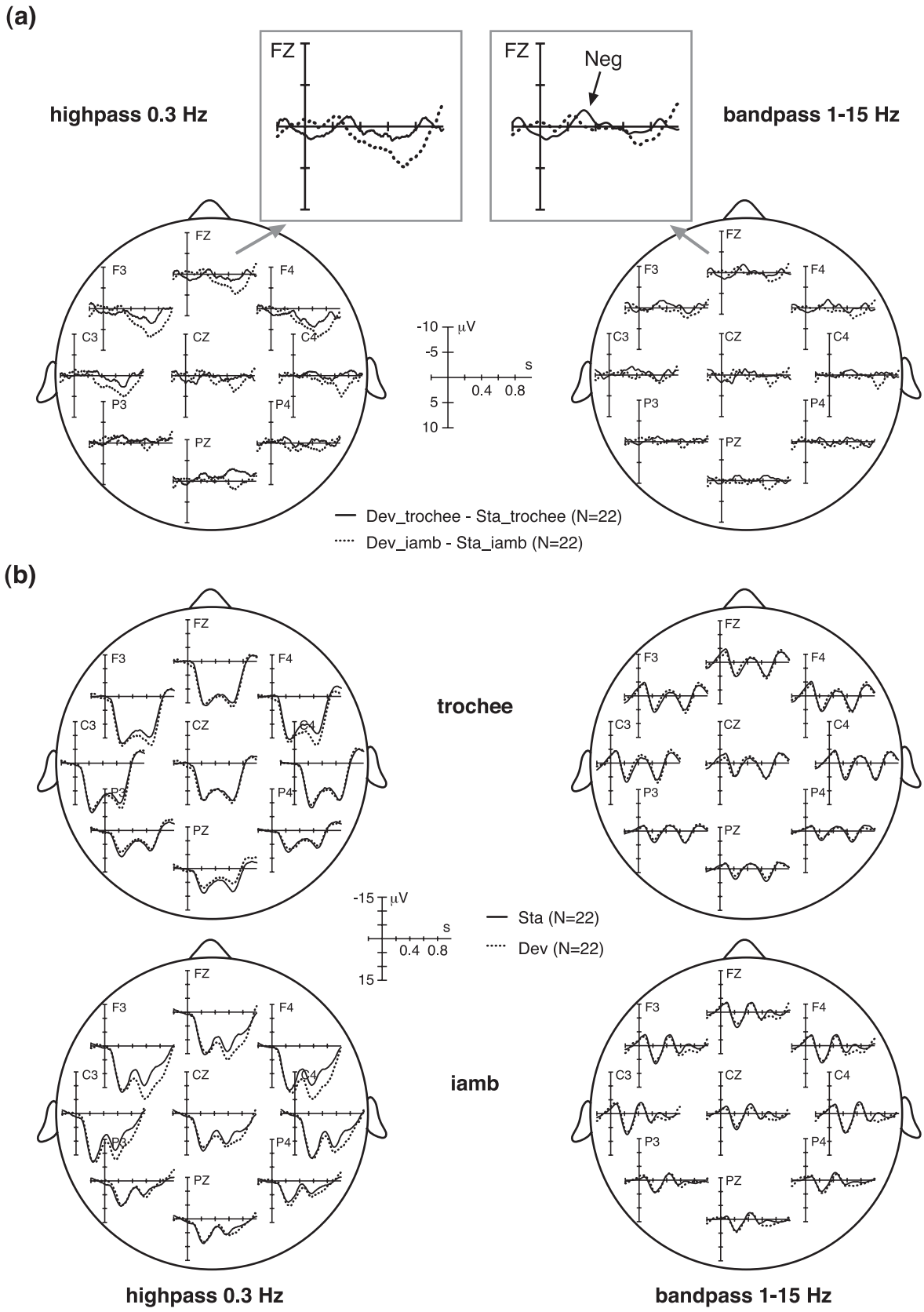


Fig. 4. (a) Grand-average difference waves (deviant minus standard) in 4-month-olds ($N = 22$). Left: data filtered with 0.3 Hz highpass. Right: data filtered with 1–15 Hz bandpass. (b) Grand-average waves for deviant and standard for the trochee condition (upper row) and for the iamb condition (bottom row). Note that scaling in (b) is different from scaling in (a).

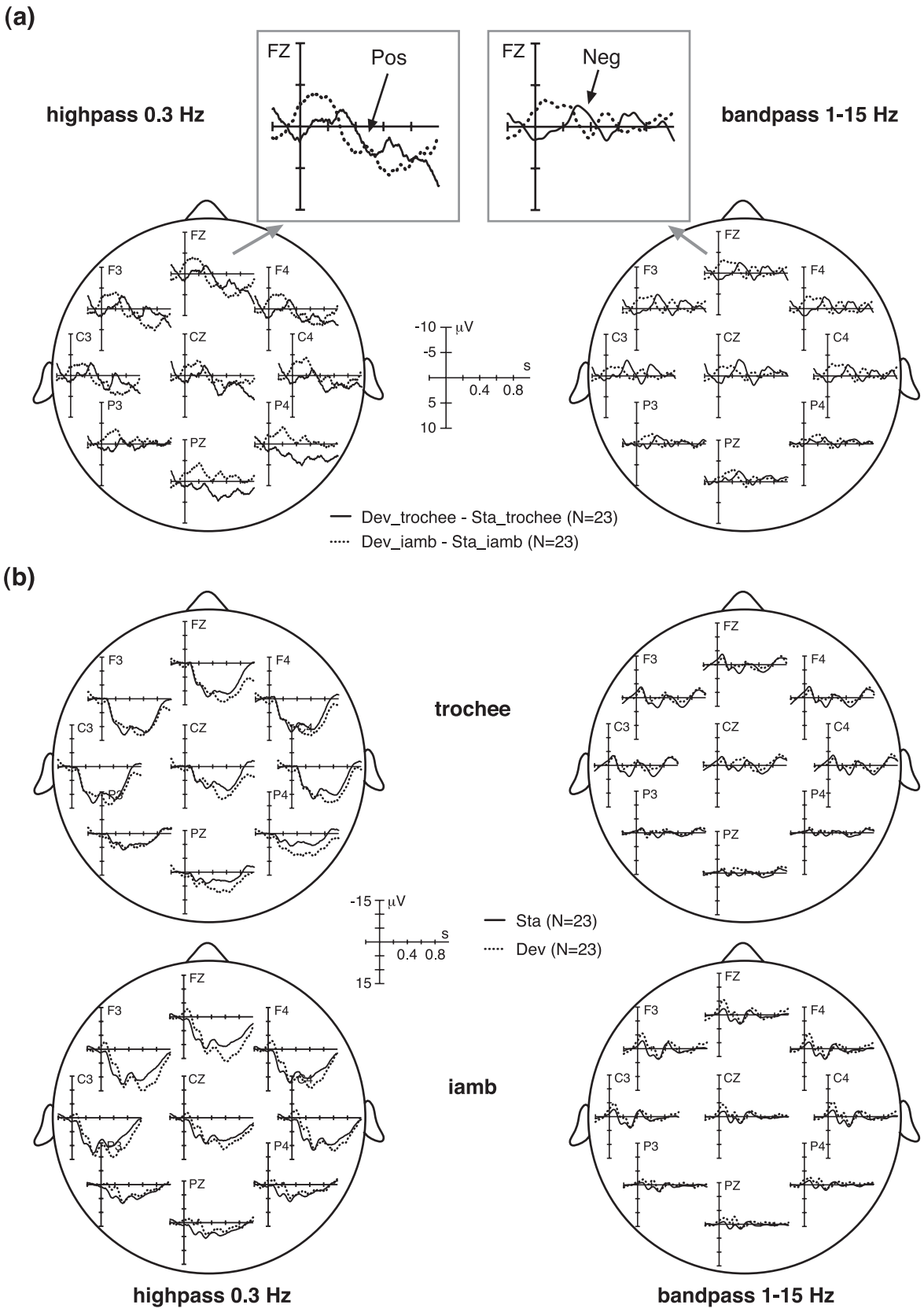


Fig. 5. (a) Grand-average difference waves (deviant minus standard) in 5-month-olds ($N = 23$). Left: data filtered with 0.3 Hz highpass. Right: data filtered with 1–15 Hz bandpass. (b) Grand-average waves for deviant and standard for the trochee condition (upper row) and for the iamb condition (bottom row). Note that scaling in (b) is different from scaling in (a).

C3, Cz, C4; posterior: P3, Pz, P4) were performed when a Mismatch Response was seen. Hemispheric effects were tested in the same way as in Experiment 1. The Greenhouse–Geisser correction was applied when evaluating effects with more than one degree of freedom in the numerator. In the following we report uncorrected degrees of freedom and corrected probabilities.

3.5. Results and discussion

Fig. 4b displays the grand average of ERPs in 4-month-olds for the trochee and the iamb condition after applying a highpass filter of 0.3 Hz (left) and a bandpass filter of 1–15 Hz (right).

Fig. 4a (left) shows the grand-average difference waves after application of the highpass 0.3 Hz filter in 4-month-olds. When the deviant stimulus was the trochaic item, visual inspection suggested a negatively displaced peak at about 330 ms which was discernible at fronto-central sites. However, two positive peaks at about 430 ms and at about 630 ms were much more prominent. When the iambic item was the deviant stimulus, a small negatively displaced peak at about 240 ms was observed at fronto-central sites. Again, the more prominent wave was a positivity peaking at about 690 ms at fronto-central sites. None of the described effects were statistically significant for either condition ($p < 0.1$). No effects of Gender were found.

In Fig. 4b (right), the grand-average difference waves for the same infant data are displayed after application of the 1–15 Hz bandpass filter. Visual inspection indicated that the negative peak around 330 ms, which was elicited by the trochaic deviant stimulus, was more prominent with the 1–15 Hz filter. Its distribution as well as its latency ressembled the MMN elicited by the trochaic deviant stimulus in adults. On the contrary, the positivity was obviously now less pronounced. The iambic deviant item elicited a small negative deflection at 240 ms which was seen again after application of the 1–15 Hz bandpass filter. Again, the positivity was clearly reduced after the bandpass filter was applied. None of these apparent effects, however, were statistically significant. Hence, neither the iambic nor the trochaic pseudoword was reliably discriminated by German infants at the age of 4 months.

4. Experiment 3: 5-month-olds

4.1. Materials and methods

4.1.1. Participants

In Experiment 3, recordings were taken from 20-week-olds (0 ± 5 days). General inclusion criteria were the same as in Experiment 2. A total of 33 infants (16 female) completed both runs of the experiment with the required number of accepted deviant items. Ten infants (five female) were excluded from further analyses as they spent most of the experimental time in quiet sleep. In total, 23 infants (11 female; mean gestational age: 39.95 weeks, mean conceptual age: 59.44 weeks) participated in Experiment 3. *T*-tests revealed significant differences of conceptual age between the infant group participating in Experiments 2 and 3 ($p < 0.001$). Five infants spent the whole experimental time in awake state, 18 infants were in mixed states, i.e. changes between awake and active sleep stage were observed.

4.2. Stimuli and procedure

Stimuli and procedure were the same as in Experiment 2.

4.3. EEG recording

EEG recording was the same as in Experiment 2. Impedances were below 10 kΩ.

4.4. Data analysis

Data analyses was the same as in Experiment 2.

4.5. Results and discussion

Fig. 5b displays the grand average ERPs in 5-month-olds for the trochee and the iamb condition after applying a highpass filter of 0.3 Hz (left) and a bandpass filter of 1–15 Hz (right).

Fig. 5a (left) shows the difference waves for both conditions in 5-month-old infants obtained after applying the highpass 0.3 Hz filter. After visual inspection, again, a negativity peaking at about 320 ms followed by a positivity at about 500 ms was seen for the trochaic deviant item. In

Table 4a
Differences between ERP responses to deviant and standard in German infants (5 months old, $N = 23$)

0.3 Hz highpass	*df*	*t*1	*t*2
ms		275–355	460–540
Dev_trochee–Sta_trochee			
Discrimination	1.21		6.44*
Discrimination × Site	8.168	1.79	
Discrimination × Gender	1.21		
Gender	1.21		
		275–355	360–440
Dev_iamb–Sta_iamb			
Discrimination	1.21		
Discrimination × Site	8.168	1.56	1.00
Discrimination × Gender	1.21		3.51
Gender	1.21		

Time windows (*t*) in ms relative to stimulus onset. All *F*-values larger than 1.00 are reported. **$p \leq 0.01$; ***$p \leq 0.001$.

*$p \leq 0.05$.

comparison to the ERPs obtained in 4-month-olds (Fig. 4), the negativity was more pronounced in the older infants. However, between-condition-comparisons only revealed a main effect for Discrimination at 460–540 ms, i.e. for the positivity starting at 400 ms after change onset, indicating a positive MMR for the trochaic deviant stimulus (Table 4a). Neither topographic nor gender differences were revealed. Visual inspection suggested that the iambic deviant stimulus elicited a negativity at around 200 ms as well as a positivity peaking at about 400 ms. However, statistical analyses did not reveal any significant effect for the iambic deviant item (Table 4b). Thus, the discrimination related positive response was only seen for the trochaic item in German 5-month-olds.

In Fig. 5a (right), difference waves for both conditions obtained in the same 5-month-olds after applying the 1–15 Hz filter are displayed. For the trochaic deviant stimulus, again, a prominent negativity was identified at about 320 ms. It was followed by a smaller positivity at about 500 ms. Between-condition-comparisons revealed a significant main effect for Discrimination at 275–355 ms, i.e. at the same latency as MMN was seen in adults (Table 4b). No hemispheric differences were observed. A significant interaction between Discrimination and Region was found for central versus posterior sites [275–355 ms: $F(1,22)=4.32$, $p<0.05$]. One-way ANOVAs for the latter sites indicated a more centrally distributed effect [central: $F(1,22)=10.78$, $p<0.01$; posterior: $F(1,22)=5.87$, $p<0.05$]. For the iambic deviant item, a negativity was detected at about 200 ms. A positivity was observed at around 400 ms. However, no statistical significant discrimination related effect was revealed when the iambic item functioned as the deviant stimulus. Thus, a discrimination related negative response was only seen for the trochaic two syllable item in infants as old as 5 months.

Table 4b
Differences between ERP responses to deviant and standard in German infants (5 months old, $N=23$)

1–15 Hz bandpass	*df*	*t*1	*t*2
ms		275–355	460–540
Dev_trochee–Sta_trochee			
Discrimination	1.21	9.13**	3.42
Discrimination × Site	8.168	2.09	1.59
Discrimination × Gender	1.21		1.92
Gender	1.21	3.83	
		275–355	360–440
Dev_iamb–Sta_iamb			
Discrimination	1.21		1.32
Discrimination × Site	8.168		
Discrimination × Gender	1.21		2.98
Gender	1.21		1.24

Time windows (*t*) in ms relative to stimulus onset. All *F*-values larger than 1.00 are reported. ***$p\leq0.001$.
**$p\leq0.01$.

5. General discussion

In the present experiments, evoked responses to trochaic and iambic two syllable items in 4- and 5-month-old infants as well as in adult controls were recorded in a mismatch paradigm. Additionally, the possible impact of different filter settings on the morphology of the mismatch response in infants was evaluated.

In adults, MMN was seen for the trochaic as well as for the iambic deviant stimulus, indicating discrimination of both stress patterns. No hemispheric differences were observed. Infants at the age of 4 months were not able to discriminate either the trochaic or the iambic deviant item. Infants at the age of 5 months, however, were able to discriminate the trochaic deviant stimulus from the iambic standard, indicating a developmental change in discrimination abilities for the trochaic stress pattern. The negative discrimination response appeared at the same latency as in adults, i.e. between 175 and 255 ms after change onset. The present finding for the trochaic deviant item is in line with an earlier study showing MMR to vowel differences in 3-month-old infants at about the same latency as adults [4].

As reviewed in the Introduction, different studies on infants' sensitivity to phoneme and syllable discrimination by means of a mismatch negativity paradigm reported either a negativity as a mismatch response or a positivity. As these studies varied in their filter setting, we presented our data with two different filter settings in order to allow a more direct comparison of these studies.

In adults, ERP effects did not differ as a function of filter setting, but infant ERPs did.

In both the 4- and 5-month-old infants, a negativity was observed when the 1–15 Hz bandpass filter was applied, but not when the filter was set at 0.3 Hz. Rather, with highpass filtering at 0.3 Hz, a significant positive MMR starting at 360 ms after change onset was observed for the 5-month-olds. This result clearly demonstrates the importance of filter setting in the analysis of infant ERP data. In general, it is known that infant EEGs show a considerable amount of slow wave activity during all vigilance states between 2 and 12 months [43]. The specific finding reported for the highpass 0.3 Hz filter may be due to a significant overlap of slow wave activity, possibly related to the positive MMR, and higher frequencies (e.g. mismatch negativity related theta waves) [1,47].

A positive mismatch response with a latency of about 300–400 ms after deviance onset has been reported before in infant studies [13,15,20,45]. One suggestion is that this positivity reflects a genuine change detection response which might be due to developmental features of infant ERPs [33,34]. Others proposed that an increased obligatory response to the physically different deviant item, in comparison to the standard, relates to the positive MMR observed in infants [2]. Alternatively, the positivity found at fronto-central sites was considered a P3a, which reflects automatic detection of novelty, even when the subject is not

actively attending to the stimulus [4,8]. This is plausible only under the assumption that a P3a is also observable during sleep, as a prominent positive discrimination response was found in infants at the age of 2 months during quiet sleep [20].

Concerning the observed negativity after bandpass filtering, it should be noted that there is a number of studies which report negative brain responses in a MMN paradigm for infants [3,5,35]. Such negativities were found for the discrimination of vowel differences in one-syllable items in 3- and 6-month-old infants [3,5] and for the discrimination of consonant duration in two syllable stimuli only in 6-month-olds [35]. However, there is one previous study using two syllable items which reports an early MMR already in newborns (starting at 150 ms after deviance onset) [32]. This study, similar to the present one, used a bandpass filter (1–15 Hz). One reason for which no such MMR was found in the 4-month-olds in the present study could be the difference in the complexity of the stimuli used. Whereas the aforementioned study tested phoneme discrimination in infants, the present experiment investigated stress pattern discrimination which might develop later in life.

6. Conclusion

With respect to the stress patterns investigated here, the finding that both MMR responses, i.e. negativity and positivity, are only observable for the trochaic item by the age of 5 months, is crucial. The fact that 2-month-olds are able to discriminate a long syllable among short syllables but not vice versa, suggests that the trochaic item consisting of a long syllable at its onset could, most generally, be perceptually more salient and thus more easily discernible [20]. Another possible, more language specific explanation could be based on the fact that the trochaic stress pattern is more frequent in the target language and, therefore, might be detected more easily by infants at this age. However, in order to be able to distinguish between these two explanations, a cross-language study including a language with a different stress pattern needs to be conducted.

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