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Does intra-uterine language experience modulate word stress processing? An ERP study

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A R T I C L E I N F O

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A B S T R A C T

Background: Preterm birth is associated with various risks, including delayed or atypical language development. The prenatal start of prosodic tuning may affect the processing of word stress, an important suprasegmental feature of spoken utterances.
Aim: Our study focused on the expected contribution of intra-uterine experience to word stress processing. We aimed to demonstrate the hypothesized effect of intra-uterine sound exposition on stress sensitivity.
Method: We recorded ERP responses of 34 preterm infants elicited by bisyllabic pseudo-words in two oddball conditions by switching the stress pattern (legal vs. illegal) and role (standard vs. deviant).
Results: The mismatch responses found were synchronized to each syllable of the illegally stressed stimuli with no difference between pre- and full-term infants. However, the clear role of the preterm status was demonstrated by the exaggerated processing of the native stress information. The impact of intra-uterine exposure to prosody was confirmed by our finding that moderate-late preterm infants outperformed the very preterm ones.
Conclusion: Intra-uterine exposition to prosodic features appears to contribute to the emergence of stable long-term stress representation. When this tuning is missing it is considered a risk for the language acquisition process.

What does this paper add?

It is crucial to investigate preterm infants' development for at least two reasons: (1) premature birth is becoming more prevalent; (2) even in the absence of any known brain injury, preterm birth has an effect on various higher-level cognitive functions and results

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in an atypical developmental trajectory. Maturity measures of language acquisition are good markers when infants at risk of delayed language acquisition need to be identified. This is the first study to use the ERP method to investigate the effect of shorter intra-uterine language experience on word stress processing. Our data clearly demonstrate how important it is to investigate the development of word-level native stress processing as a crucial factor in early word segmentation.

Previous studies have demonstrated the disadvantageous effect of shortened intra-uterine exposition to spoken language in the first few months after birth. Our study demonstrates that the effects of this shortened intra-uterine language experience on stress processing can also be registered in the second half of the first year of life. Unlike in previous studies, our findings indicate that the prosodic processing of preterm infants born after 30 weeks of gestation with no obvious structural brain abnormalities is also atypical. The most significant outcome of our study is that the severity of prematurity appears to alter prosodic processing, which plays a pivotal role in early language acquisition.

1. Introduction

Newborns have a wide range of universal linguistic abilities and perceptual sensitivities. These inborn skills guide infants' first steps in the acquisition of the phonological elements of their mother tongue, such as relevant speech sounds, phonotactic rules, intonation contour of sentences, and the word's stress pattern (Friederici, 2005). Numerous studies have shown that the discrimination capacity between different phoneme categories is present quite early on (Dehaene-Lambertz & Dehaene, 1994). Friederici and Wessels (1993) demonstrated that 9-month-old infants are already sensitive to phonotactic constraints on word boundaries.

The prosodic structure of spoken utterances is salient from birth (Cooper & Aslin, 1990; Sambeth, Ruohio, Alku, Fellman, & Huotilainen, 2008). This also means infants have an acute ability to discriminate language-specific word stress patterns in the presence of limited segmental variability (Sansavini, Bertoncini, & Giovanelli, 1997). However, sensitivity to intonational phrase boundaries develops during the first year of life (Pannekamp, Toepel, & Alter, 2005). Word stress perception in infancy has been examined in several studies by means of the Mismatch Negativity (MMN) event-related brain potential (ERP) component (Friederici, Friedrich, & Christophe, 2007; Garami, Ragó, Honbolygó, & Csépe, 2014). The results suggest that stress processing relies not only on salient acoustic features but also on long-term stress representation at an age of as early as 6 months (Garami et al., 2014).

Segmentation of continuous speech into meaningful elements is a challenging task for infants if there is no lexical segmentation strategy (Christophe, Dupoux, Bertonici, & Mehler, 1994). The characteristic stress patterns used in the child's native language play a significant role in word segmentation, both in variable-stressed (e.g. English) and in fixed-stressed languages like Finnish and Hungarian. According to the prosodic bootstrapping hypothesis (Nazzi & Ramus, 2003), sensitivity to the stress pattern of the native language underlies an efficient language-specific segmentation procedure. The extraction of the trochaic units results in an efficient prosodic segmentation procedure in English infants at the age of 7.5 months (Cutler & Norris, 1988), just as in fixed stress languages, such as Hungarian.

Only a few studies have investigated the language perception abilities of preterm (PT) infants at the electrophysiological level, even though various empirical data suggest they are at risk of atypical language development. The study of Paquette et al. (2015), which examined preterm infants at three months of age, revealed that preterm infants' compromised discrimination performance is focused more on linguistic stimuli (syllable discrimination) than on non-speech stimuli. Atypical perceptual narrowing was associated in PT infants with slower language acquisition (Jansson-Verkasalo et al., 2010). The authors found that whereas the full-term infants lost their sensitivity to discriminate non-native phonemes at 6–12 months of age, prematurely-born infants showed remarkable sensitivity to these phonemes even at the end of their first year of life. The authors attributed these results to atypical tuning of the brain to native language phonemes. In line with this study, Peña et al. (2012) suggest that the formation of phonological representations by the child's environment is strongly constrained by brain maturation factors.

According to studies by Ragó, Honbolygó, Róna, Beke, and Csépe (2014) and Gonzalez-Gomez and Nazzi (2012), the developmental patterns in the acquisition of prosody and phonotactic information are different. In their study, Ragó et al. (2014) did not find any differences between preterm and full-term infants at the same chronological age in relation to phoneme contrast discrimination, although differences were found in the amplitude of the mismatch responses with regard to stress pattern discrimination. The authors concluded that two cortical networks differ in maturation as a result of the diverse impact of the intra-uterine language experience. Gonzalez-Gomez and Nazzi (2012) found that consonant-based phonotactic acquisition is indexed by listening age rather than maturational age, which determines the development of prosodic processing.

According to Gonzalez-Gomez and Nazzi (2012) there are 6 factors which could explain atypical prosodic development in PT infants: (1) PT infants need more time to learn prosodic features due to maturational differences; (2) the quality and amount of input varies; (3) prosodic sensitivity is impaired; (4) there are cerebral white matter microstructural problems; (5) it is the result of cascading effects, as the typical developmental timing of the brain is altered and some subcomponents do not develop within the typical time period or at the typical speed. The authors attribute the prosodic developmental delays to one other factor in particular, i.e. (6) the loss of prenatal experience. This relates to the concept of Gervain (2018), who proposed that prenatal experience with speech may play a more important role in language development than previously believed. In the following sections we will review the most important findings in relation to these possible explanations/factors.

According to previous studies very early postnatal experience does not have a compensatory effect on perception of acoustic features and speech (Bisiacchi, Mento, & Suppiej, 2009; Pena, Pittaluga, & Mehler, 2010; Peña, Werker, & Dehaene-Lambertz, 2012; Therien, Worwa, Mattia, & DeRegnier, 2004). The findings of the study conducted by Pena et al. (2010) reinforce the view that the early period of language acquisition is mainly determined by maturational age. The issue of whether early extra-uterine language stimulation provides over-stimulation or effective compensation for overcoming the effects of prematurity is still a controversial one

(Hüppi et al., 1996).

One possible explanation for later neurodevelopmental consequences in very/moderate-late PT infants is the presence of white matter microstructural alterations (Giménez et al., 2008; Hinojosa-Rodríguez et al., 2017; Kelly et al., 2016). However, the results of empirical studies do not exclusively attribute the atypical language development of the PT infants to white matter structural abnormalities (Foster-Cohen, Friesen, Champion, & Woodward, 2010). Furthermore, Counsell et al. (2008) did not report a significant correlation between language performance and the white matter microstructural abnormalities registered at term-equivalent age.

Several papers suggest that intra-uterine language exposure plays an important role in tuning the auditory system for native language prosody. Prenatal auditory attunement is possible because hearing is operational from about the 20th week of gestation (Eggermont & Moore, 2012), and prosody is preserved despite the low-pass filtering effect of the womb. In her review, Gervain (2018), pointed out that the segmentation of continuous speech into meaningful elements is one of the first uses of prenatally-acquired prosodic knowledge. She hypothesizes that PT infants' language development will be delayed or transitorily disrupted if there is an absence of prenatal prosodic experience. Her review provides empirical evidence to support the notion that prenatal prosodic learning allows infants to use prosody to bootstrap the acquisition of grammar and the lexicon (Gervain, 2018). Furthermore, in line with the explanation of Gonzalez-Gomez and Nazzi (2012) regarding the atypical development of prosodic perception in PT infants, several studies have emphasized that atypical word stress perception of PT infants can be attributed to shorter in utero exposure to native language (Herold, Höhle, Walch, Weber, & Obladen, 2008; Ragó et al., 2014).

The majority of studies on PT-related cognitive development are confined to infants of very/extremely pre-term status in spite of the high proportion of late and moderate PT infants (Shapiro-Mendoza & Lackritz, 2012). Nevertheless, moderate-late PT infants are also at a higher risk of cognitive impairment than their full-term (FT) peers. For these reasons we decided to focus our study on moderate-late and very preterm infants.

In the present study, we used the same method and stimuli as Honbolygó and Csépe (2013) did with adults and Garami et al. (2014) did with FT infants. We tested the stress perception in a passive oddball paradigm by measuring the mismatch negativity ERP component (for review see Näätänen, Paavilainen, Rinne, & Alho, 2007). The study was designed to investigate the effect of the length of intra- and extra-uterine language experience on emerging long-term stress representation, as shown by the developmental changes of word stress processing. We expected different MMN pattern in PT group as a result of shortened intra-uterine language experiences. Reduced intra-uterine experience might cause altered long-term stress representation, consequently influences ongoing word stress processing.

Furthermore, we hypothesized that PT infants' long-term native stress representation would be more unstable than that of FT infants and that they would provide different responses to the acoustically identical stimulus (legal stress pattern) in standard and deviant role in the oddball paradigm. Bisiacchi et al. (2009) attribute an important role to the degree of prematurity in relation to auditory processing. We hypothesized lower word stress differentiation in the very PT infants (which in this study means 30–32 weeks of gestation) than in the moderate-late PT infants (33–36 weeks of gestation).

2. Materials and methods

2.1. Participants

Thirty-four PT infants participated in the study (mean gestation age (GA) = 32.82 weeks, range = 30–36 weeks, mean birth weight = 1908 g, range = 1120–2660 grams). To study the effect of the severity of prematurity, we divided them in two groups: moderate-late PT infants (n = 17; mean corrected age in days: 224.88; mean GA: 34.41, range = 33–36 weeks of gestation) and very PT infants (n = 17, mean corrected age in days: 262.47; mean GA: 31.24, range = 30–32 weeks of gestation, see Table 1).

The average length of intra- and extra-uterine life is illustrated in Fig. 1. In accordance with the generally accepted clinical consensus (Lems, Hopkins, & Samsom, 1993), the PT infants' age was corrected to the expected date of delivery (corrected age). PT infants were therefore measured at 6 months (mean age in days: 190.16, SD: 5.47) and at 10 months of corrected age (mean age in days: 312, SD: 3.66). Furthermore, Ragó et al. (2014) tested PT infants at the same age without correction, which also provides an insightful comparison to understand the maturation of the PT infants' language processing. Twenty-two additional infants were tested but excluded from the final analysis due to fussiness (n = 2), technical problems (n = 3), or a low number of artifact-free trials (below 40, n = 17). The inclusion criteria were (1) normal cerebral ultrasound (2) no asphyxic incident (3) raised in a monolingual

Table 1
Descriptive statistics of the moderate-late and very preterm infants' groups (PT: preterm; SD: standard deviation).

	6-month-old infants (N = 19)	10-month-old infants (N = 15)	Corrected age in days M (SD)	Postnatal age in days M (SD)	Birth weight M (SD)	Gestational age M (SD)
Moderate-late PT infants (N = 17)	N = 12	N = 5	224.88 (59.059)	264 (57.7)	2092.4 (337.338)	34.41 (0.939)
Very PT infants (N = 17)	N = 7	N = 10	262.47 (59.299)	323.82 (58.859)	1723.82 (238.56)	31.24 (0.831)
Statistical comparison			F (1,33) = 3.429 *p* = 0.073	F (1,33) = 8.955 *p* = 0.005	F (1.33) = 13.568 *p* = 0.001	F (1.33) = 109.009 *p* = 0.000

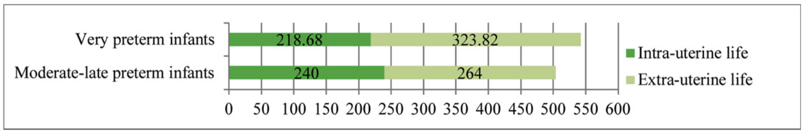

Fig. 1. Graphical illustration of the length of intra- (dark green) and extra-uterine (pale green) life separately by the two PT groups. Duration of the pre- and postnatal life is presented in days.

language environment (4) no chromosome malformation (5) normal hearing, and (6) appropriate birth weight for gestation age.

In order to obtain a comparable dataset, we matched our participants to those of the study of Garami et al. (2014) by age. They measured FT infants (N = 48, mean GA = 39.2 range 37–41 weeks of gestation, mean birth weight = 3384, range: 2370–4900 grams) in two age groups: 6 months (N = 21) and 10 months (N = 27) (for the details of these two age groups see Table 2). The inclusion criteria were (1) raised in monolingual language environment (2) normal hearing (3) no neurological impairment or (4) any known developmental delay.

One-way ANOVA revealed no significant differences between the maturational age of PT and FT infants (6 month-olds: F (1, 27.85) = 1.497 $p = 0.231$; 10 month-olds: F (1, 31) = 1.638 $p = 0.21$). There was a significant difference between the PT and the FT group in terms of postnatal age F (1, 81) =4.971 $p = 0.029$. However, ANOVAs for the GA differences between PT and FT groups showed that the GA was significantly different F (1, 54.307) = 317.806 $p < 0.001$ (6 month-olds: F (1, 39) = 152. 317 $p <$ 0,001; 10 month-olds: F (1, 19.43) = 154.95 $p < 0.001$). Moreover, no significant difference was found between the corrected age of the moderate-late PT infants and the very PT infants' group F (1, 33) = 3.429 $p = 0.073$. The main descriptive statistics of the PT and FT infants' age groups are shown in Table 2. The participating families were recruited from the Department of Developmental Neurology at the Szent Margit Hospital in Budapest. The participating infants' parents gave their written consent to the experiment in accordance with the World Medical Association's Declaration of Helsinki prior to the data being collected. The electrophysiological experiment was approved by ENKK 007217/1/2016/OTIG and by the Ethical Board of the Szent Margit Hospital. The experiment was conducted at the hospital, where a portable EEG recording system (BrainAmp from BrainProducts GmbH) was used, the same as the one used in the study by Garami et al. (2014) on FT infants.

2.2. Stimuli and experimental conditions

The experimental design was the same as the one used for adults (Honbolygó & Csépe, 2013) and FT infants (Garami et al., 2014). Two bisyllabic pseudo-words were presented with different stress patterns ('BE-be', 'be-BE', capital letters indicate stress). The repetition of the same syllable allowed the creation of a stimulus with identical segmental content but different prosodic properties. The stressed and unstressed syllables differed in their maximal intensities (84.5 vs. 82 dB) and maximal f0s (170 vs. 155 dB). For the legal stress pattern the first syllable is stressed and the second is unstressed, whereas for the illegal stress pattern the first syllable is unstressed the second is stressed; for further details see Honbolygó and Csépe (2013). In Hungarian, word stress is realized by changes in both intensity and pitch (Varga, 2002), and stress is always on the first syllable of the word (except for in compound words) and it is characterized by high regularity (Siptár & Törkenczy, 2007). Thus, while the 'BE-be' pattern is considered legal, the 'be-BE' pattern, with stress on the second syllable, is deemed illegal.

2.2.1. Procedure

Stimuli were presented in a passive oddball paradigm with a stimulus onset asynchrony (SOA) varying randomly between 730 and 830 ms. The stimuli lasted for 539 ms. We used two conditions identical to the study performed on the FT infants: 1) illegal deviant condition: the pseudo-word with the legal stress pattern was the standard stimulus, and the pseudo-word with the illegal stress pattern was the deviant stimulus; 2) legal deviant condition: the roles of the stimuli were reversed, the pseudo-word with the illegal stress pattern became the standard, and the pseudo-word with the legal stress pattern became the deviant stimulus. In each condition stimuli were presented in four blocks in a quasi-random order. Each block began with at least ten standard stimuli, and deviants were separated by at least one standard stimulus. The probability of the deviant stimuli was 20% (n = 200). The order of the two

Table 2
Participants included in the statistical analysis (PT: preterm; FT : full-term; SD: standard deviation). The data for full-term infants were collected by Garami et al. (2014).

	PT 6 months of age (n=19) M (SD)	PT 10 months of age (n=15) M (SD)	FT 6 months of age (n=21) M (SD)	FT 10 months of age (n=27) M (SD)
Postnatal Age (days)	238 (15.38)	364.2 (12.68)	193.86 (12.61)	315.33 (14.91)
Corrected Age (days)	190.16 (5.47)	311.47 (3.66)	–	–
Birth weight (grams)	1963 (361.55)	1838 (316.90)	3400 (481.92)	3372 (602.24)
Gestational Age (weeks)	33 (1.73)	33.5 (1.96)	39.24 (1.41)	39.33(1.14)

conditions presented to the participants was counterbalanced (legal first vs. illegal first). The average recording time was about 12 min. Participants were sitting on their mother's lap and were kept calm by being given stuffed toy animals and puppets. Stimuli were presented via a loudspeaker (Soundkey MS-310, 70 dB) placed at a distance of approximately 100 cm from the participants. The stimulation was performed using the Presentation software (v 12.1). The session lasted 45 min in total, including preparation and pauses.

2.3. Data collection and measurement

The electroencephalogram was recorded from 16 scalp locations: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, O2, T3, T4, M1, M2. The reference electrode was at Cz, and the ground was between Fz and Fpz on the midline. The electrodes were arranged in accordance with the international 10–20 system. The sampling rate was 500 Hz. The online filter was 0.3–70 Hz. The offline data analysis was performed using BrainVision Analyzer software (BrainProducts GmbH). The original EEG was algebraically re-referenced to the average activity of the two mastoid electrodes. A band-pass filter of 0.5–20 Hz, 12 dB/octave was used. The raw EEG data were segmented into epochs of 800 ms, time-locked to the onset of the stimulus (−100 ms before onset to 700 ms after onset). Electrophysiological responses to the deviant stimuli and to the standard preceding them were used for analysis. An automatic artifact rejection method with +/− 150 μV constraint within a sliding window of 300 ms was applied for every channel.

Based on the previous findings for FT infants, two time windows of 100 ms were selected for the 300–400 and 450–550 ms intervals of the responses recorded over the frontal electrode sites (F3, Fz, F4). Honbolygó and Csépe (2013) used the same stimuli in adults and their data confirmed that the MMN had a longer latency to this stimulus type when compared with the typical latency range of this response, peaking at 100–250 ms from the change onset (Näätänen et al., 2007).

2.4. Statistical analysis

We first assessed the mismatch responses. We performed a 3 × 2 × 2 × 2 mixed ANOVA with within-subject factors Electrode (Fz, F3, F4) and Role (standard vs. deviant) and between-subject factors Age (6 vs. 10 months) and Gestation status (preterm vs. full-term) separately for the two conditions (illegal deviant condition, legal deviant condition) and for the two latency windows. If any of the between-subject factors were significant, difference amplitudes of the mismatch responses were calculated for all groups (deviant minus standard on the individual EEG data).

To confirm the impact of Legality, responses to the stimuli of legal and illegal stress in standard vs. deviant role were compared across conditions. For this we performed a 3 × 2 × 2 × 2 mixed ANOVA with within-subject factors Electrode (F3, Fz, F4), Role (standard vs. deviant), Legality (legal vs. illegal stress pattern), and between-subject factor Age and Gestation status (preterm vs. full-term).

Furthermore, another factor called degree of Prematurity (Prematurity Index) was included and calculated using the PT infants' data, hence we performed a 3 × 2 × 2 × 2 × 2 mixed ANOVA with within-subject factors Electrode (F3, Fz, F4), Role (standard vs. deviant), Legality (legal vs. illegal stress pattern), and between-subject factors Age and Prematurity Index (very preterm infants vs. moderate-late preterm infants).

The significant interactions were further analyzed by Post Hoc ANOVA-s. All multiple comparisons were adjusted by the Bonferroni correction.

3. Results

3.1. Illegal deviant condition

We assumed that the two large deflections present on the difference curves were genuine mismatch responses (MMR) reflecting the processing of word stress changes related to the first and second syllables of the pseudo-words. While the first MMR reflected the detection of missing stress on the first syllable of the deviant, the additional stress on the second syllable elicited the second MMR. This assumption is based on the study of Honbolygó and Csépe (2013).

3.1.1. First time window (300–400 ms)

In the first time window we found that Role $F\,(1, 78) = 8.423$ $p = 0.005$ $\mu^2 = 0.097$ $\beta = 0.818$ had a significant main effect. The effect was due to the fact that the deviant elicited a more positive deflection than the standard stimulus (Fig. 2a). Furthermore, we found that Gestation status $F\,(1, 78) = 7.604$ $p = 0.007$ $\mu^2 = 0.089$ $\beta = 0.77$ also had a significant main effect. In order to interpret the Gestation status main effect, we calculated the degree of MMR in all channels by deviant-standard subtraction. The MMRs were compared by performing a mixed ANOVA where within-subject factor Electrode (F3, Fz, F4) and between-subject factor Gestation status were used with no significant effect for Gestation status ($p = 0.894$). These results imply no difference in the MMR amplitudes between the PT infants and FT infants' group (Fig. 2b). The significant main effect for Gestation status can therefore be explained by the fact that MMR polarity for the PT infants' group was more positive than that of the full-term infants.

3.1.2. Second time window (450–550 ms)

As in the first time window, the main effect of the Role was significant $F\,(1, 78) = 14.103$ $p = 0.000$ $\mu^2 = 0.153$ $\beta = 0.96$ (Fig. 2b). This effect was caused by the positive deviation in the deviant role matched to the standard role. The main effect of Age was

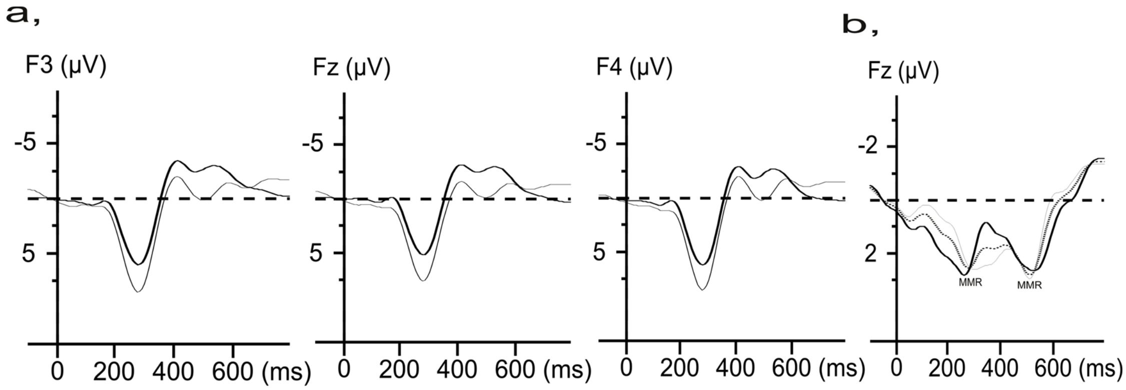

Fig. 2. All infants' ERP results in the illegal deviant condition. **a)** Grand average ERPs to the standard of legal stress (black thick line) and to the deviant of illegal stress (black thin line) over three frontal electrodes. **b)** Grand average difference waves of all infants (dashed line) and the PT (thick black line) and FT infants (black thin line) on Fz.

also significant F (1, 78) = 4.193 p = *0.044* $\mu^2 = 0.051$ $\beta = 0.53$. The significant Age main effect can be explained by the fact that polarity of the 10-month-old infants was more positive in general than that of the 6-month-old infants (Fig. 3). To validate this possibility we calculated the degree of mismatch responses in all channels by deviant-standard subtraction. The MMRs were compared by performing a mixed ANOVA where within-subject factor Electrode (F3, Fz, F4) and between-subject factor Age were used with no significant effect for Age (p = *0.352*) (Fig. 4). These results imply no difference in the MMR amplitudes between the PT infants and FT infants.

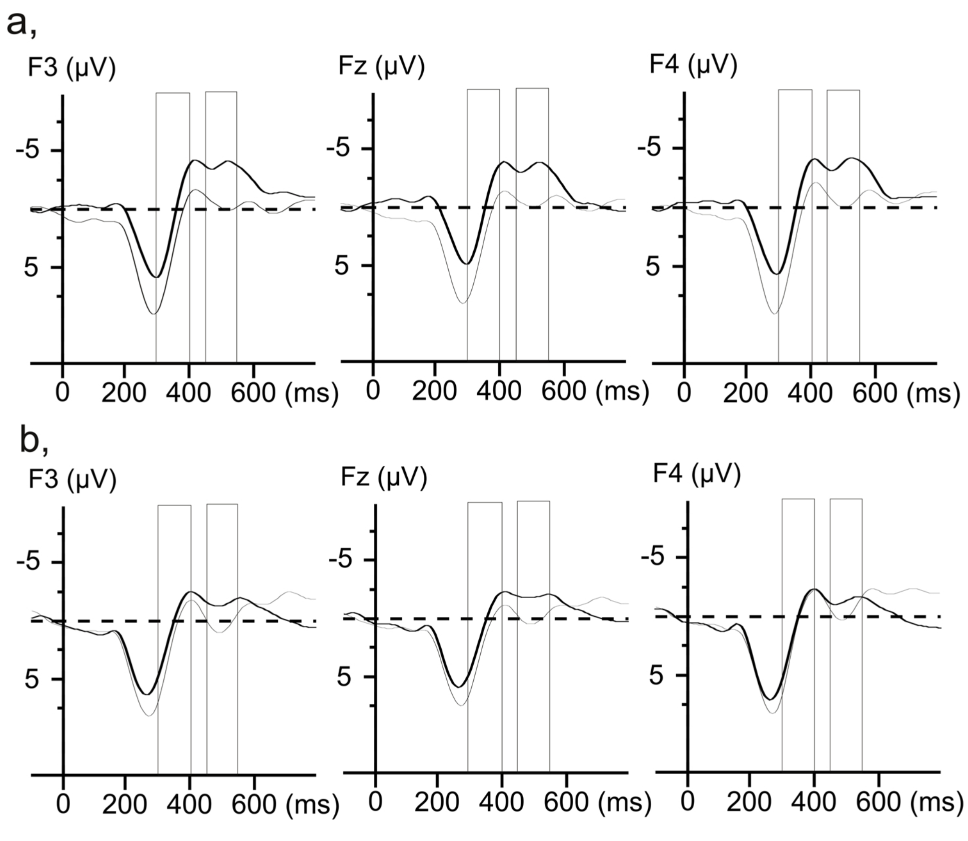

Fig. 3. ERP results in the illegal deviant condition. **a,** Standard (thick line) and deviant (thin line) grand average curves computed in the 6-month-old group (PT and FT) at the three electrode sites. **b,** Standard (thick line) and deviant (thin line) grand average curves computed in the 10-month-old group (PT and FT) at the three electrode sites. The time windows where significant positive mismatch responses were found (300–400), (450–550) are signaled.

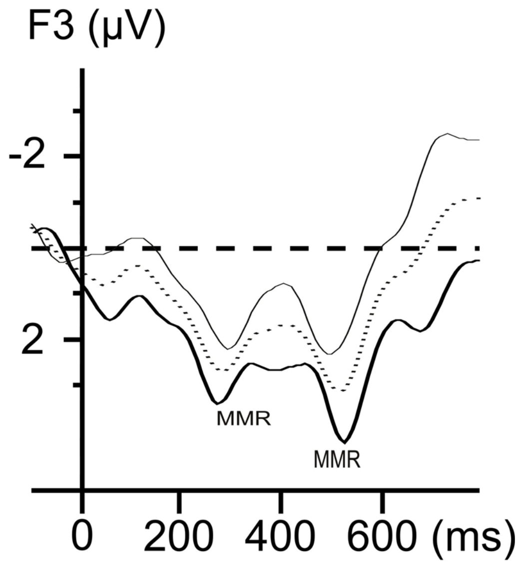

Fig. 4. Grand average difference waves obtained by subtracting the ERPs to the legal standard from the ERPs to the illegal deviant stimuli of all infants (all groups) (dashed line) and the 6-month-old infants (thick line) vs. 10-month-old infants (thin line) on F3 electrode.

3.2. Legal deviant condition

In the legal deviant condition, we expected that the immature stress processing in the PT infants' group would result in MMR responses. The mixed design ANOVA revealed significant differences between the ERPs of standard and deviant in the first time-window, regardless of the Gestation status. We assume that this MMR reflects the detection of the stress on the first syllable of the deviant; however, the absence of stress on the second syllable of the deviant did not elicit the mismatch response.

3.2.1. First time window (300–400 ms)

In the first time window Role was found to have a significant main effect F (1, 78) = 4.982 $p = 0.028$ $\mu^2 = 0.060$ $\beta = 0.60$. The standards elicited significantly positive ERP responses than that of the deviants (Fig. 5a). These results imply no difference in the MMR amplitudes between the PT and FT infants (Fig. 5b).

3.2.2. Second time window (450–550 ms)

The statistical results confirmed the lack of MMR components in this latency window, as none of the within-subject factors had any main effects (Role: $p = 0.585$). The Gestation status main effect proved to be significant F (1, 78) = 10.386 $p = 0.002$ $\mu^2 = 0.118$ $\beta = 0.89$. However, if we compare the MMR differences with a mixed design ANOVA as described above, the Gestation status ($p = 0.881$) proved to be insignificant. The ERP results of this condition for the 10-month-olds and 6-month-olds are presented in Figs. 6 and 7.

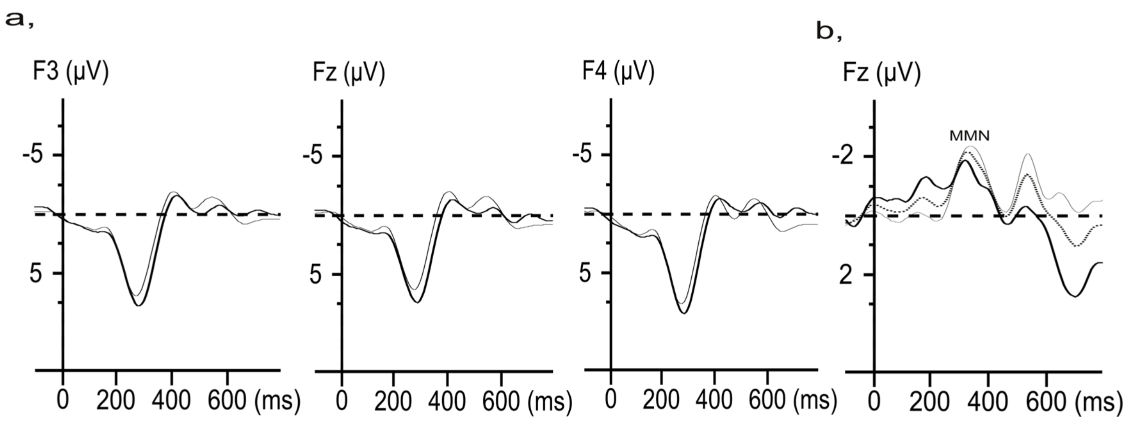

Fig. 5. All infants' ERP results in the legal deviant condition. **a)** Grand average ERPs to the standard of illegal stress (black thick line) and to the deviant of legal stress (black thin line) over three frontal electrodes. **b)** Grand average difference waves of all infants (dashed line) and the PT (thick black line) and FT infants (black thin line) on Fz.

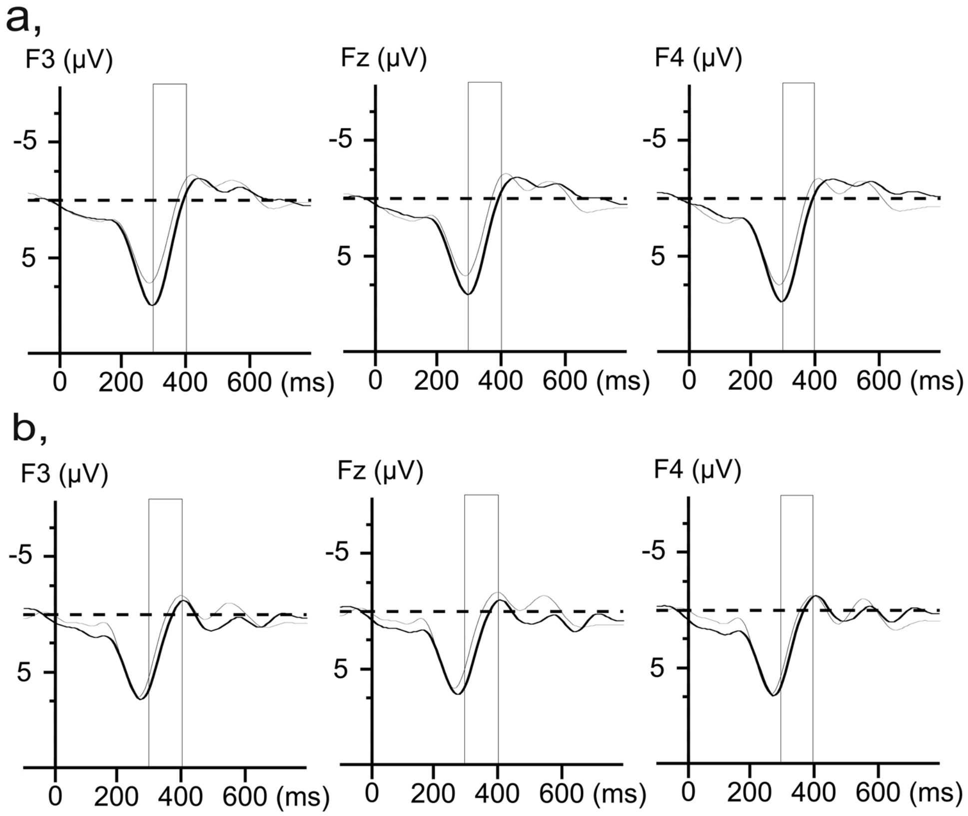

Fig. 6. ERP results in the legal deviant condition. **a,** Standard (thick line) and deviant (thin line) grand average curves computed in the 6-month-old group (PT and FT) at the three electrode sites. **b,** Standard (thick line) and deviant (thin line) grand average curves computed in the 10-month-old group (PT and FT) at the three electrode sites. The time window where significant negative mismatch response was found (300–400) is signaled.

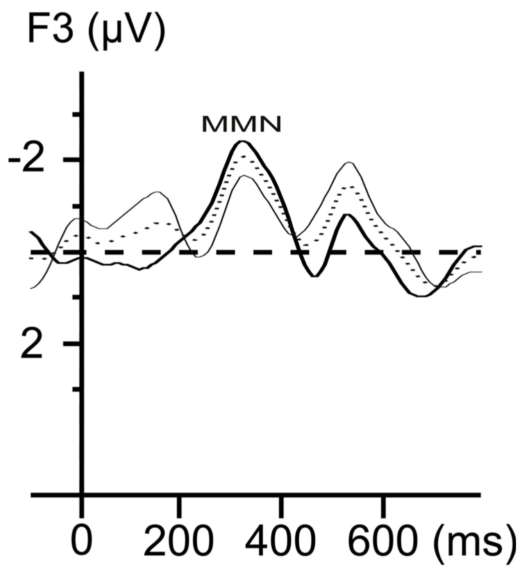

Fig. 7. Grand average difference waves obtained by subtracting the ERPs to the illegal standard from the ERPs to the legal deviant stimuli of all infants (all groups) (dashed line) and the 6-month-old (thick line) vs. 10-month-old infants (thin line) on F3 electrode.

3.3. Legality effect

This additional analysis was used to test the stability of long-term stress representation. We analyzed the ERPs for legal and illegal stress patterns in different roles and various stress patterns in the same role.

3.3.1. First time window (300–400 ms)

We found a main effect for Legality F (1, 78) = 12.227 $p = 0.001$ $\mu^2 = 0.136$ $\beta = 0.93$, and the illegal stress pattern elicited significantly larger amplitude deflection than the legally stressed pattern. The Electrode main effect was significant F (2, 77) = 4.254 $p = 0.018$ $\beta = 0.73$, and larger amplitude was registered on the F3 electrode than on the Fz electrode. The Gestation status main effect was significant F (1, 78) = 5,650 $p = 0.020$ $\beta = 0.65$. However, if we compare the MMR components with the mixed design ANOVA described above, the Gestation status was not significant in either of the difference waves.

3.3.2. Second time window (450–550 ms)

We found a main effect for Role F (1, 78) = 5.558 $p = 0.021$ $\mu^2 = 0.067$ $\beta = 0.64$, as the standards elicited significantly more negative ERPs than the deviants. There was also a main effect for Legality F (1, 78) = 8.237 $p = 0.005$ $\mu^2 = 0.096$ $\beta = 0.81$, as the legal stress pattern elicited more negative amplitude deflections than the illegal ones. Marginally significant interaction was found between Role x Legality F (1, 78) = 3.863 $p = 0.053$ $\mu^2 = 0.047$ $\beta = 0.50$. The interaction between Electrode x Age was significant F (2, 77) = 3.137 $p = 0.049$ $\mu^2 = 0.075$ $\beta = 0.59$. The Post hoc ANOVA-s revealed that in the 10-month-old infants' group, significantly more negative ERPs were registered on the Fz electrode than on the F3 electrode. We did not find significant differences between the ERPs of the three electrode sites in the 6-month-old infants' group. Furthermore, Age F (1, 78) = 6.050 $p = 0.016$ $\mu^2 = 0.072$ $\beta = 0.68$ and Gestation status were significant F (1, 78) = 8.558 $p = 0.005$ $\mu^2 = 0.099$ $\beta = 0.82$. However, if we compare the MMR components with the mixed design ANOVA described above, neither the Gestation status nor the Age were significant in any of the difference waves.

3.4. Effect of the prematurity index

This additional analysis was introduced to test the stability of long-term stress representation in the PT infants and the effect of the Prematurity index (severity of the PT status). We analyzed the ERPs to the legal and illegal stress pattern in different roles, and different stress patterns in the same role.

We calculated a 3 × 2 × 2 × 2 × 2 (Electrode x Role x Legality x Prematurity Index x Age) ANOVA in the two time windows separately.

We found a main effect for Legality F (1, 30) = 4.283 $p = 0.047$ $\mu^2 = 0.125$ $\beta = 0.52$ and significant Role x Prematurity Index interaction F (1, 30) = 4.719 $p = 0.038$ $\mu^2 = 0.136$ $\beta = 0.56$ in the first time window. A further analysis performed by separate post hoc ANOVAs revealed significantly more positive ERPs to deviants than to standards F (1, 16) = 4.728 $p = 0.045$ $\mu^2 = 0.228$ $\beta = 0.53$ in the moderate-late PT infants' group. However, in the very PT group no main effect was found for Role F (1, 16) = 1. 52 $p = 0.236$ $\mu^2 = 0.087$ (see Fig. 8).

In the second time window (450–550) we found a main effect for Role F (1, 30) = 4.852 $p = 0.035$ $\mu^2 = 0.139$ $\beta = 0.57$ and main effects for Legality F (1, 30) = 5.170 $p = 0.03$ $\mu^2 = 0.147$ $\beta = 0.59$ and Age F (1,30) = 5.902 $p = 0.021$ $\mu^2 = 0.164$ $\beta = 0.65$, as well as Role x Legality interaction F (1, 30) = 5.964 $p = 0.021$ $\mu^2 = 0.166$ $\beta = 0.66$ and Role x Electrode x Prematurity Index interaction F (2, 29) = 3.932 $p = 0.031$ $\mu^2 = 0.213$ $\beta = 0.66$. The Role effect was significant as the deviants elicited significantly more positive ERP deflections than the standards. Concerning the Legality main effect, the illegally stressed pseudo-words elicited a significantly larger amplitude response than the legally stressed ones. The Age main effect did not prove to be significant in any of the difference waves. A post hoc ANOVA on the Role x Legality interaction revealed significantly more negative amplitudes to the standards of legal stress than to the standards of illegal stress F (1, 33) = 14.324 $p = 0.001$ $\mu^2 = 0.303$ $\beta = 0.96$. The legally stressed pseudo-word in the standard role elicited a more negative response than the one in the deviant role F (1, 33) = 10.604 $p = 0.003$ $\mu^2 = 0.243$ $\beta = 0.84$ and the illegal stress in deviant role F (1, 33) = 14.465 $p = 0.001$ $\mu^2 = 0.305$ $\beta = 0.96$ (Fig. 9). This amplitude difference

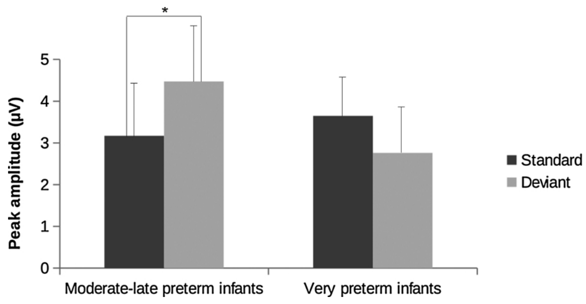

Fig. 8. Illustration of the Prematurity Index x Role interaction over the frontal electrodes in the first time window; *: $p < 0.05$.

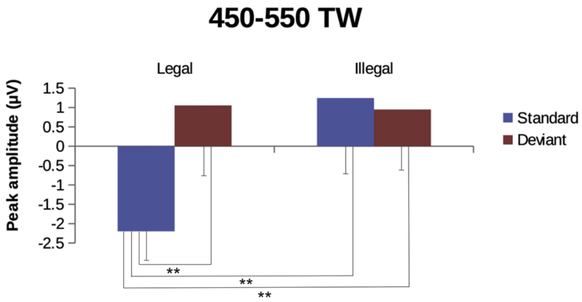

Fig. 9. Illustration of the Role x Legality interaction of the PT infants' data over the frontal electrodes; TW: time window. **: p < 0,01.

Table 3
The significant main effects and interactions in the PT and FT groups..

Group	300-400 ms time window	F and p values	450-550 ms time window	F and p values
Preterm infants	Legality main effect	*F* (1,30) =4.283 *p*= *0.047*	Legality main effect 193.86 (12.61)	*F* (1,30) =5.170) *p*= *0.030*
	Role x Prematurity Index	*F* (1,30) = 4.719 *p*=*0.038*	Role main effect	*F* (1,30) =4.852 *p* =*0.035*
			Age main effect	*F* (1,30)=*5.902* *p*=*0.021*
			Role x Electrode x Prematurity index	*F* (2,29)= *3.932* *p*=*0.031*
			Legality x Role	*F* (1,30) = 5.964 *p*= *0.021*
Full-term infants	Legality main effect	*F* (1,46)= 8.069 *p*= *0.007*	–	–
	Role x Legality	*F* (1,46)= 4.088 *p*=*0.049*	–	–
	Electrode x Age	*F* (2,45)=3.649 *p*=*0.034*		

resulted in an MMR in the illegal deviant condition for the second latency window. No significant differences were identified between the deviant roles of illegal and legal stress patterns F (1, 33) = 0,011 p = *0.917* μ^2 = 0.00. We also did not find any differences between the ERP amplitudes of the legally stressed deviant and the illegally stressed standard stimulus F (1, 33) = 0.05 p = *0.824* μ^2 = 0.002, and the responses to illegal stress presented in different roles F (1, 33) = 0.122 p = *0.729* μ^2 = 0.004 did not show significant differences either (Fig. 9). Table 3 summarizes the main effects and interactions of the two Gestation groups.

3.5. Full-term infants' data

In the first time window, we found a significant main effect for Legality *F (1.46)* =8.069 p = 0.007, significant Role x Legality interaction *F (1.46)* =4.088 *p* = *0.049* and significant Electrode x Age interaction *F (2.45)* =3.649 *p* = *0.034*. In the second time window there was no significant main effect (see Table 3).

4. Discussion

We examined word-level stress processing in PT and FT infants aged 6 and 10 months using pseudo-words. ERPs elicited by two acoustically identical pseudo-words of legal and illegal stress were presented in a passive oddball paradigm as both standard and deviant. Sensitivity to stress violation was assessed by measuring the MMR component to legal and illegal stress assignment. In order to investigate the expected impact of intra– and extra-uterine exposure on the maturation of acoustic contrast and linguistic representations, the ERP data of PT infants was compared to those acquired in an identical experimental set up for FT infants. In addition, we assessed the effect of prematurity level on early acoustic and linguistic processing.

In the *illegal deviant condition,* where pseudo-words with legal stress pattern were rarely interspersed with the same pseudo-words but with illegal stress, a significant MMR occurred in the first (300–400) and second time window (450–550). Regarding the MMR amplitudes, no differences were found between the Gestation status and age groups. This indicates that PT and FT infants successfully distinguish the illegal stress pattern of pseudo-words from frequent legal ones regardless of their age. Furthermore, these results are similar to those found in adults (Honbolygó & Csépe, 2013) as well as in infants (Friederici et al., 2007; Garami et al., 2014).

Herold et al. (2008) and Ragó et al. (2014) found that FT infants' stress discrimination performance exceeded that of the PT infants. The study of Bisiacchi et al. (2009) revealed the maturational factor (severity of prematurity) had a significant effect on auditory discrimination. Based on their conclusion, we could attribute the difference between our results and those of Herold et al. (2008) to the maturity difference, as these authors examined very PT infants (< 30 weeks of gestation). In our study, we examined moderate PT infants of a broader range of birth weight.

It was not unexpected that our outcome differed from the study of Ragó et al. (2014), as they used meaningful words and examined their PT infants at the same chronological age as their FT infants. It is well demonstrated that lexical status enhances the comparison of prosodic information (Garami, Ragó, Honbolygó, & Csépe, 2017) and that the amplitudes of the mismatch responses are highly influenced by whether the syllables are presented in a pseudo-word/word context (Pulvermüller et al., 2001). Unlike Ragó et al. (2014), who tested PT and FT infants at the same chronological age, we tested whether longer extra-uterine language experience (PT infants age were corrected) in PT infants (compared to FT infants) could compensate for the shortened intra-uterine one.

We found a mismatch positivity, which is interpreted as immature MMR (Trainor et al., 2003) and associated with different listening strategies and even with the different generators (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). Furthermore, it is also suggested that this mismatch positivity is the infant analogue of the adult P3 (Kushnerenko, Kushnerenko, C, & C. A. R., 2002). Friedrich, Weber, and Friederici (2004) proposed that positivity is elicited when more effortful perceptual processes are needed, implying less-well established memory structures.

In the *legal deviant condition,* the legally stressed stimulus was used as deviant, which elicited an MMR of negative polarity in the first time-window. In this condition, we did not find a significant difference in the amplitude of the mismatch responses between the PT and FT infants' groups. Mismatch response patterns are not in parallel in this condition with those of adults in the study of Honbolygó and Csépe (2013). According to the general view on the generation of the mismatch response, this component reflects both the sensory trace and the long-term representations of regularities and higher-level rules (Winkler & Schröger, 2015). We concluded that the long-term representation of native stress pattern is still emerging in this period of development, thus stress processing is only partly influenced by the long-term native stress template and partly led by salient acoustical features.

PT infants spent a significantly longer amount of time in extra-uterine life than FT infants (as their age was corrected to the expected date of delivery). In the mismatch settings the statistical analysis did not reveal differences between the two groups (PT vs. FT). In line with previous studies (Gonzalez-Gomez & Nazzi, 2012; Pena et al., 2010), these results imply that prosodic processing in PT infants is mainly determined by their maturational age (corresponding to their postnatal age minus the duration of their prematurity) rather than by their chronological age. Our findings confirm the results of previous studies (DeRegnier, Wewerka, Georgieff, Mattia, & Nelson, 2002) in the sense that PT infants definitely need longer extra-uterine language experience in order to compensate for the immaturity of their brain.

Despite the presence of sensitivity to illegal and legal stress regardless of the Gestation status (PT vs. FT) main effect, these results do not indicate that processing is intact in PT infants, as revealed in our more in-depth analyses in which we specifically examined the stability of long-term stress representation.

We found that the legal stress occurring in different roles (standard, deviant) elicited different ERP amplitudes in the second time window in PT infants. This was probably due to the lack of representational stability. This indicates a maturational lag when the results of the FT infants are taken into account showing that full-terms processed the legal stress regardless of its role in the oddball paradigm. According to Friedrich, Herold, and Friederici (2009), this result means that the native language deviant is processed with a different level of effort to the native language standard. This is attributed to the insufficiently stable memory structures of the native language stimulus. If these are stable, they allow effortless processing regardless of whether they are activated frequently or not. In their experiment, Friedrich et al. (2009) found that atypical stress processing in infants recorded with ERPs is reflected in poor expressive language skills. The unstable long-term stress representation of the PT infants does probably have implications for speech segmentation skills and vocabulary growth; however our study directly examined the stress perception of the PT infants. Our results are in line with Ragó et al. (2014) who suggest that word stress processing is compromised in PT infants, implying that they have difficulties with acquiring an important phonological detail of their target language.

The unstable long-term stress representation of PT infants could be explained by two different hypotheses (Gonzalez-Gomez & Nazzi, 2012). (1) Differences in the period of exposure to the input (intra and extra-uterine). The FT infants in our experiment had around 254 days of extra-uterine exposure, plus about 20 weeks of intra-uterine exposure (hearing is operational from about the 20th week of gestation), whereas the PT infants had approximately 50 more days of exposure in the extra-uterine language environment with around 7 weeks less in-utero experience. We argue that if the extra-uterine auditory stimulation compensated the early maturational lag, PT infants' long-term stress representation would have been as stable as that of their FT peers. It is questionable whether auditory stimulation is sufficient in the postnatal period (Hüppi et al., 1996), or whether neural immaturity constrains the effect of the external stimulation. According to some authors (Fellman et al., 2004; Gonzalez-Gomez & Nazzi, 2012; Herold et al., 2008), if the in utero language experience is shortened, the longer and richer extra-uterine language environment will not be able to expand its advantageous effects. Our argument reinforces the third proposal of Gonzalez-Gomez and Nazzi (2012) who propose that (2) PT infants exploit prosody information less than phonotactics/phonology, resulting in a delay in prosodic acquisition as PT infants have less intra-uterine language experience (Gonzalez-Gomez & Nazzi, 2012). This hypothesis is supported by Mahmoudzadeh et al. (2017), who found that the phoneme-sensitive cortical network is already functional at thirty weeks of gestation without specific experience (Peña et al., 2012).

As expected, increasing gestational age was associated with better stress discrimination. While we did not find any differences between the ERPs to standards and deviants in the very PT infants, we obtained significantly different responses in the moderate-late PT infants. In general, we can conclude that the lower the severity, the better the stress discrimination is. This result reinforces our previous arguments in two respects. First, it implies that extra-uterine language experience is inefficient (due to immaturity and inefficient auditory stimulation) in relation to prosodic development (the very PT infants spent a significantly longer amount of time (323 days) in postnatal life at the time of measurement compared to the moderate-late PT infants who spent 264 days in postnatal life). However, the very PT infants in our study spent less time in-utero, so their auditory system is not tuned to the native language's prosodic properties to the same extent. Second, this result supports the hypothesis that the length of the intra-uterine language experience plays a more important role in prosodic perception than the effects of the extra-uterine language experience. The prenatal interval can also be interpreted as a sensitive period for prosodic development. This result is not surprising if we consider the studies which have found evidence of fetuses' hearing abilities (Abrams & Gerhardt, 2000), and the low-pass filtering effect of the womb. Our results expand on the findings of Bisiacchi et al. (2009) as we found that the severity of prematurity influences the discrimination of linguistic stimuli. Furthermore, we identified that the severity of prematurity has measurable implications for the perception of prosody in the second half of the first year of life.

With regard to our first hypothesis about the MMN changes, we did not find any differences in either of the two conditions at the same maturational age of PT and FT infants. However, our second hypothesis was reinforced by our findings. The native stress pattern in different roles elicited different amplitude deflections in the PT infants group in the absence of stable long-term native stress representation. Our third hypothesis about the severity of prematurity was confirmed by our results. The moderate-late PT infants' stress discrimination was more mature compared to that of the very PT infants group at the same corrected age. Our results emphasize the prominent role of the intra-uterine language experience in tuning the auditory system for native language prosody.

Declarations of interest

None.

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