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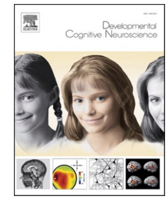

Longitudinal trajectories of electrophysiological mismatch responses in infant speech discrimination differ across speech features

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ABSTRACT

Infants rapidly advance in their speech perception, electrophysiologically reflected in the transition from an immature, positive-going to an adult-like, negative-going mismatch response (MMR) to auditory deviancy. Although the MMR is a common tool to study speech perception development, it is not yet completely understood how different speech contrasts affect the MMR's characteristics across development. Thus, a systematic longitudinal investigation of the MMR's maturation depending on speech contrast is necessary. We here longitudinally explored the maturation of the infant MMR to four critical speech contrasts: *consonant*, *vowel*, *vowel-length*, and *pitch*. MMRs were obtained when infants ($n = 58$) were 2, 6 and 10 months old. To evaluate the maturational trajectory of MMRs, we applied second-order latent growth curve models. Results showed positive-going MMR amplitudes to all speech contrasts across all assessment points that decreased over time towards an adult-like negativity. Notably, the developmental trajectories of speech contrasts differed, implying that infant speech perception matures with different rates and trajectories throughout the first year, depending on the studied auditory feature. Our results suggest that stimulus-dependent maturational trajectories need to be considered when drawing conclusions about infant speech perception development reflected by the infant MMR.

1. Introduction

Born with the ability to discriminate speech sounds (Dehaene-Lambertz and Pena, 2001; Partanen, Pakarinen et al., 2013), infants' receptive language development rapidly advances during their first year of life. A common measure for infants' speech discrimination abilities is the electrophysiological Mismatch Response (MMR). The MMR signals neural change detection processes and is obtained by contrasting the electrophysiological response to a *standard* stimulus with the response to a rare *deviant* (Näätänen et al., 1978, 2007). While adults' MMR is typically negative (i.e., mismatch negativity, MMN/n-MMR; Näätänen et al., 2007; Näätänen and Alho, 1997), positive MMRs are often observed in infants (p-MMR; He et al., 2009; Ruusuvirta et al., 2003; Winkler et al., 2003). It has been proposed that infants' MMR can be divided into two distinct components, a positive and a negative deflection with varying latencies (Friederici et al., 2002; Friedrich et al., 2004; He et al., 2007; Kushnerenko et al., 2002; Leppänen et al., 1997). The p-MMR is thought to indicate enhanced attentional demands associated with auditory change detection early in life (Cheng et al., 2015; Friederici et al., 2007), while the n-MMR may be related to infants' perceptual attunement to the speech contrasts of their native language. During the attunement to native sound categories, native contrasts begin to predominantly elicit n-MMRs, while non-native contrasts elicit less mature p-MMRs (Friedrich et al., 2009; Garcia-Sierra et al., 2016; Rivera-Gaxiola et al., 2005). Thus, during language development, as infants gain more experience with native speech sound discrimination

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leading to reduced attentional demands, the amplitude of the p-MMR decreases, while the n-MMR's amplitude increases as a result of infants' native-language attunement (Garcia-Sierra et al., 2016). This results in a shift from the observed p-MMR in infants to the n-MMR in children and adults (Cheng et al., 2013; He et al., 2007; Kushnerenko et al., 2002; Trainor et al., 2003). The infant MMR and its development from a p-MMR to an n-MMR is commonly used to draw conclusions on speech perception development in infancy and beyond (Cheng et al., 2015; Friedrich et al., 2009; Mueller et al., 2012; Pena et al., 2012; Weber et al., 2004). However, despite the general development from p-MMR to n-MMR, the MMR's characteristics are also influenced by experimental features (e.g., interstimulus-interval (ISI), attentional demands of the design), language background, and stimulus features (Cheng et al., 2013, 2015; Garcia-Sierra et al., 2016; Leppänen et al., 1999; Morr et al., 2002; Sambeth et al., 2009). Consequently, depending on design and stimulus features, either p- or n-MMRs have been found for comparable age groups across different studies (e.g., Cheour, Ceponiene et al., 1998; Kailaheimo-Lönnqvist et al., 2020; Pihko et al., 1999; Ragó et al., 2014; Schaadt et al., 2015). Crucially, design and stimulus features not only influence single-time-point MMR amplitudes, but also differently affect the MMR's maturational trajectory (e.g., Cheng et al., 2015; Garcia-Sierra et al., 2016). Additionally, the pace of native-language attunement, reflected in increasingly more negative MMR amplitudes, is feature-dependent (e.g., vowels, consonants; Tsuji and Cristia, 2014). Therefore the MMR to different features may transit to an n-MMR at different ages, potentially adding to the inconsistent findings on the MMR's development depending on language background and speech feature. Taken together, although the MMR is frequently used to study speech perception and its development in infancy, the effect of different speech contrasts, language backgrounds and experimental features on the MMR's characteristics is not well understood. To reliably explore these effects, systematic longitudinal studies of the MMR's maturation are needed. To our knowledge, there have been few longitudinal studies on infant MMRs to speech contrasts, mostly studying one or two speech contrasts across two time points (Cheng et al., 2013; Pihko et al., 1999; Schaadt et al., 2015). Yet, focusing on two isolated points in time ignores the relevance of studying the shape of developmental trajectories for understanding key aspects of developmental processes (Grimm et al., 2011). Additionally, examining several speech features while controlling for other influencing factors (e.g., language background, experimental design) would allow for a detailed understanding of the MMR's feature-dependent development. Taken together, a systematic study of infant MMRs to several speech features across multiple assessment points is missing. This, however, seems mandatory for a fine grained understanding of speech perception development in infancy.

The present study longitudinally investigated the maturation of German-learning infants' MMR to different speech contrasts in the first year of life. The MMR was elicited in a multi-feature paradigm with syllables deviating in *consonant*, *vowel-length*, *pitch/frequency* and *vowel* from a *standard* syllable at 2, 6, and 10 months of age. Second-order latent growth curve models were applied to evaluate the maturational trajectory of the infant MMR to different *deviants*, allowing for linear as well as non-linear progressions.

Based on previous findings in German-learning infants (Friederici et al., 2002; Friedrich et al., 2004, 2009; Schaadt et al., 2015), we expected all *deviants* to elicit a p-MMR at 2 months, followed by an amplitude decline towards a more mature n-MMR at 6 and 10 months. However, we hypothesised different maturational rates depending on stimulus features. As the MMR's maturation has been suggested to reflect native-language attunement (Garcia-Sierra et al., 2016; Rivera-Gaxiola et al., 2005), which occurs earlier to vowels than to consonants (Polka and Werker, 1994; Tsuji and Cristia, 2014; Werker and Lalonde, 1988), we expected the *vowel* MMR amplitude to decline faster than the *consonant* MMR. We also predicted the *frequency* and *vowel-length* MMR amplitudes, two prosodic cues (Höhle et al., 2009; Wellmann et al., 2012), to mature (i.e., decrease) earlier than MMRs to phoneme changes (i.e., *consonant* and *vowel*), because infants attune to their native language's prosody prenatally (Abboub et al., 2016; Mehler et al., 1998). As vowel-length is also phonemically relevant in German (Maurer, 2014; Reed, 1965), whereas frequency is not (Wang et al., 2007), we expected differences in the maturational rate between *frequency* and *vowel-length* MMRs, yet without any specific predictions given the lack of previous longitudinal studies here.

2. Methods

2.1. Participants

Infants were recruited from the Infant Database of the Max Planck Institute for Human Cognitive and Brain Sciences Leipzig. For an infant to be included in the analyses, at least two datasets of sufficient quality [i.e., a minimum of 50 % (= 400) artifact-free trials] had to be available from all assessment points (t_1, t_2, t_3). According to this criterion, sixteen infants had to be excluded. One additional infant was excluded due to poor eyesight. The final sample size was $n = 58$ (29 girls). Infants' *mean (M)* age was 2.28 months [*Standard Deviation (SD)* = 0.26] at t_1, 6.71 months (*SD* = 0.32) at t_2, and 10.54 months (*SD* =0.27) at t_3. All infants were born full-term (gestation week > 37, *M* = 39 weeks, *SD* = 1.37) with typical birth weight (above 2500 g, *M* = 3554.87 g, *SD* = 383.82) and without any diagnosed hearing deficits or neurological problems (parental report).

2.2. Procedure

For each infant, three electroencephalography (EEG) experiments with the same paradigm and identical stimuli were conducted at age 2, 6 and 10 months in a silent, child-friendly room. Preceding the multi-feature experiments (duration: 13 min), parents received written and oral information about the study's aim and procedure and provided written informed consent. During the experiment, infants lay or sat on their parent's lap and were, if necessary, entertained using silent toys or fed by their parents. As previous studies demonstrated a reliable elicitation of the MMR in various infant sleep states (Cheour et al., 1998; Martynova et al., 2003; Sambeth et al., 2009), infants were not prevented from falling asleep during the experiment. The entire procedure lasted about 60 min. Parents were reimbursed for their travel expenses by 7.50€ and received a toy as a gift for their infants. The study followed American Psychological Association standards in accordance with the declaration of Helsinki from 1964 (World Medical Association, 2013) and was approved by the ethics committee of the Medical Faculty of the University of Leipzig (protocol number: 082/15-ek).

2.3. Paradigm and stimuli

A multi-feature paradigm with semi-synthesized syllables was applied to examine infant speech perception abilities. The syllable /ba/ was the *standard* stimulus. As *deviants*, four different syllables were created based on previous research on infants' MMRs at 2 months or younger. Specifically, the syllable /ga/ was used as the *consonant* deviant (see Cheng et al., 2015; Mahmoudzadeh et al., 2013) and the syllable /bu/ (see Cheng et al., 2015; Koerner et al., 2016) as the *vowel* deviant. For the *frequency* deviant /ba+ /, pitch was raised by + 16 Hz (see Partanen et al., 2013) and for the *vowel-length* deviant /ba:/ the vowel /a/ was lengthened by 100 ms (see Friedrich et al., 2004). Stimuli were recorded from a female German native speaker (16-bit sampling rate, 44.1 kHz digitisation) and then adjusted using Praat Version 6.0.28 (Boersma, 2001). The duration of each stimulus was set to 170 ms (except for the *vowel-length* deviant /ba:/, set to 270 ms) and a silent period of 50 ms was added before onset and after offset. All stimuli were set to the same intensity (70 dB Sound Pressure Level). F0 of all stimuli was set to 198 Hz (i.e., speaker's mean pitch across all recorded stimuli), except the *frequency* deviant /ba+ / with an F0 of 214 Hz.

A total of 800 stimuli were presented via loudspeakers using Presentation® software version 17.2 (Neurobehavioral Systems Inc, 2014). The *standard* syllable (50 % probability, i.e., 400 *standard* syllables total) and one of the *deviant* syllables (12.5 % probability per *deviant*, i.e. 100 syllables per *deviant* total) occurred in alternation with an ISI of 800 ms. Presentation order of *deviant* syllables was pseudo-randomized, with the restriction that no more than two *deviant* stimuli of the same kind appeared consecutively.

2.4. EEG recording

The EEG was recorded from 21 Ag/AgCl active electrodes attached to an elastic cap (EasyCap GmbH, Herrsching, Germany) at standard positions according to the 10–20 system. Electrooculograms were recorded from electrodes at the outer canthi of both eyes and orbital ridges of the right eye. Recordings were online referenced to CZ with a ground electrode at FP1. Electrode impedances were mostly below 10 kΩ and always under 20 kΩ. The EEG signal was amplified via BrainAmp amplifier (Brain Products, Gilching, Germany), digitised online at 500 Hz, and recorded using BrainVision Recorder version 1.21.01.02 (Brain Products, Gilching, Germany).

2.5. EEG analysis

EEG data was processed offline using the EEGLAB® toolbox (Delorme and Makeig, 2004) and MATLAB® version R2020a (The Math Works Inc, 2020). The EEG data was algebraically re-referenced from CZ to the average of both mastoids. Data were then band-pass filtered using a windowed sinc-Fir filter with a band-pass of 1–30 Hz (Kaiser window, beta = 7.857; filter order = 1208) to remove slow drifts and muscle artefacts. Subsequently, the continuous EEG was semi-automatically scanned to remove segments with coarse artefacts (i.e., abnormal values $> \pm$ 100 μV and abnormal trends exceeding a maximum slope of 100 μV/epoch and R-squared limit of 0.5), before running an independent component analysis (ICA; Makeig et al., 1996). Eye movement-related components were selected based on topography and waveform and removed from the continuous EEG that had been band-pass filtered again at 0.5–30 Hz (windowed sinc FIR-filter, Kaiser window, beta = 7.857; filter order = 824), a band-pass setting typically used for analyzing MMR (Männel et al., 2017; Schaadt et al., 2015). EEG epochs of 700 ms post-syllable-onset including a pre-stimulus baseline of 200 ms were extracted and epochs with a signal range exceeding 150 μV and abnormal trends above a maximum slope of 150 μV and R-squared limit of 0.5 were rejected from further analysis. The *mean* number of rejected epochs was 134.95 (16.87 % of all trials; SD = 94.19) at t_1, 149.11 (18.64 % of all trials; SD = 89.92) at t_2 and 124.65 (15.58 % of all trials; SD = 82.47) at t_3. Finally, individual averages for each *deviant* stimulus (/ga/, /ba+/, /ba:/, /bu/) and for the *standard* stimulus (/ba/) were calculated and grand averages were computed.

2.6. Statistical analysis

Cluster-based permutation analyses were performed using the FieldTrip® toolbox (Oostenveld et al., 2011) and MATLAB® version R2020a (The Math Works Inc, 2020). Subsequent analyses were performed with R-Studio version 3.6.3 (R Core Team, 2020) and packages "mvn" (Korkmaz et al., 2014), and "lavaan" (Rosseel, 2012).

To identify relevant time windows (TWs) and electrodes where *standard* and *deviant* ERPs significantly differed, we performed nonparametric cluster-based permutation tests (Maris and Oostenveld, 2007, $p < .05$, $\alpha = 0.05$, 1000 permutations, ≥ 2 channels minimum cluster size) for each *deviant* and assessment point separately. All electrodes except T7/T8 and all time points between 100 and 700 ms post-syllable onset were included, as the infant MMR to syllable stimuli usually has a latency > 100 ms (e.g., Cheng et al., 2013, 2015; Dehaene-Lambertz and Dehaene, 1994; Garcia-Sierra et al., 2016; Lee et al., 2012). Sample sizes across assessment points were $n = 50$ at t_1, $n = 53$ at t_2 and $n = 51$ at t_3. Based on the cluster-based permutation results, three TWs were chosen (per *deviant* and assessment point) for the subsequent second-order growth curve models (SGMs). Three TWs were used for subsequent SGMs instead of peak amplitudes or mean amplitudes to account for potential changes in the MMR amplitude's shape across age. Specifically, this is because the TWs' loadings on the latent MMR variable (i.e., the contribution of each TW to the calculation of the MMR) are allowed to differ between assessment points in the SGM analyses.

TWs and electrodes for the SGM analyses were chosen from the cluster-based permutation test results according to the following procedure: 1) We identified the longest significant cluster (i.e., duration) for each *deviant* separately; this cluster could either stem from t_1, t_2, or t_3. 2) The duration of this cluster was then divided by 3, yielding for each *deviant* the individual lengths of the 3 consecutive TWs included in the SGM. By using individualised TWs for each *deviant*, we accounted for stimulus-specific differences in the MMR's duration. Please note that this approach resulted in the inclusion of TWs that were non-significant in the cluster-based permutation analysis at certain assessment points (which might have revealed MMR effects of shorter duration). This was done to capture the full picture of the infant MMR's development, as previous research had shown a developmental shift of the MMR towards a negativity (Friederici et al., 2002; Friedrich et al., 2004; Kushnerenko et al., 2002; Leppänen et al., 1997; Trainor et al., 2003), which might cause certain MMR TWs identified at younger ages to be non-significant across development. These TWs should, however, still be considered to capture the full picture of the infant MMR's development. 3) After the definition of the *deviant*-specific TW lengths, the first TW for each *deviant* was aligned with the individual cluster-onset revealed by the cluster-based permutation test for each assessment. This procedure accounted for MMR latency shifts across development. 4) Finally, neighbouring electrodes with the strongest activation in all cluster-based permutation analyses across all *deviants* and assessment points were chosen for the SGMs.

SGMs were calculated for each *deviant* to examine the maturational trajectory of the MMR to the *consonant*, *frequency*, *vowel-length*, *vowel deviants* between 2, 6 and 10 months. Prior to the SGM analyses, we tested the assumption of multivariate normality examining Mardia skewness, Mardia kurtosis and Henze-Zirkler's tests (Henze and Zirkler, 1990; Mardia, 1980; Mecklin and Mundfrom, 2005). Data were also tested for multivariate outliers. We used maximum likelihood estimation for model estimation and effect coding for scaling (Jeon and Kim, 2020; Little et al., 2006; Yang et al., 2020). Under the assumption that data were missing at random (MAR), we applied full-information maximum likelihood estimation for missing data. This way, all available information ($n = 58$) was utilised. Models were considered to fit the data if the Chi-Square test was non-significant ($p > .05$) and the root mean square error of approximation (RMSEA) was ≤ 0.06 (acceptable fit: $\leq .08$), the Comparative Fit Index (CFI) was ≥ 0.95 and the Tucker Lewis Index (TLI) was ≥ 0.95 (Hooper et al., 2008; Werner et al., 2016). First, a baseline model was established for each contrast (i.e., *consonant*, *frequency*, *vowel-length*, *vowel*), including the infant MMRs at 2, 6, and 10 months as first-order latent variables and intercept and slope as second-order latent variables. Mean amplitude differences between *standard* and *deviant* in the chosen TWs and the chosen electrode cluster were used as indicator variables. Loadings of the first-order latent variables on the intercept were fixed (to value 1), as were the first two loadings on the slope (to value 0 at 2 months and 1 at 6 months). The loading of the latent 10-month-MMR variable on the slope was freely estimated (β) to exploratively examine the specific growth trajectory over time. Covariances of MMR amplitudes across assessment points were included. First-order latent variable means were fixed to zero and variances were fixed to be equal.

Likelihood ratio tests (LRT) with the Satorra–Bentler scaled chi-squared statistic (Satorra and Bentler, 2001) were performed for model comparison. We compared the baseline models to models without the slope parameter to examine whether the MMR amplitude significantly changed over time. Subsequently, we fixed the 10-month-MMR's loading on the slope based on the estimation in the baseline model and compared the fixed-loading-models with the baseline models. Slope loadings were fixed to allow for a meaningful interpretation of growth trajectories.

Although the possibility to test measurement invariance is a major advantage of SGMs and typically applied in SGM analyses, we decided to not test our models for any type of measurement invariance. This decision was made because 1) included TWs changed across assessment points within every model and 2) we specifically expected TWs at different assessment points to differentially contribute to the calculation of the MMR, due to the developmental changes of the MMR amplitude's shape.

3. Results

3.1. Infants' discrimination of speech sounds

Fig. 1A-C illustrate the ERPs to *standard* and *deviants* respectively at ages 2, 6 and 10 months and Fig. 2 depicts the differences waves for each *deviant* type and assessment point.

From the cluster-based permutation tests, only clusters with a length > 100 ms and an MMR-typical distribution (i.e., frontocentral, see Friedrich et al., 2009; He et al., 2007; Trainor et al., 2003; Weber et al., 2004) were considered for subsequent analyses and are reported here (for additional clusters that did not fulfil these criteria, see appendix A.1). According to these criteria, we found significant positive clusters (deviant versus standard ERPs) with a frontocentral distribution for each *deviant* and each assessment point (see Table 1). Fig. 3A-C show a topographical representation of average *t*-values in the respective clusters.

3.2. Longitudinal development of infant speech discrimination

Based on the cluster-based permutation test results, we chose the electrodes with the highest *t*-values across all *deviants* and assessment points, that is, frontocentral electrodes (FC1, FC5, FC2, FC6), and three TWs for each *deviant* and assessment point. For the *consonant* contrast, the longest cluster was found at 2 months (i.e., 450 ms; resulting in a TW length of 150 ms), for the *frequency* contrast, it was found at 6 months (i.e., 176 ms; resulting in a TW length of 60 ms), for the *vowel-length* contrast, it was found at 2 months (i.e., 382; resulting in a TW length of 130 ms), and for the *vowel* contrast, it was also found at 2 months (i.e., 304 ms; resulting in a TW length of 100 ms). The specific TWs are listed in Table A.2, and violin plots depicting the interindividual variance in MMR amplitudes within these TWs are depicted in Figure A.3.

Fit indices, results from the chi-square tests, and parameter estimates of all following models are listed in Tables A.5.1 and A.5.2.

Because the assumption of multivariate normality was violated in the *frequency* and *vowel* model (see appendix A.4), we applied robust maximum likelihood estimation for the fitting of these models and report robust values. The chi-square tests were non-significant and fit indices indicated a good (*frequency, vowel-length, vowel*) or acceptable

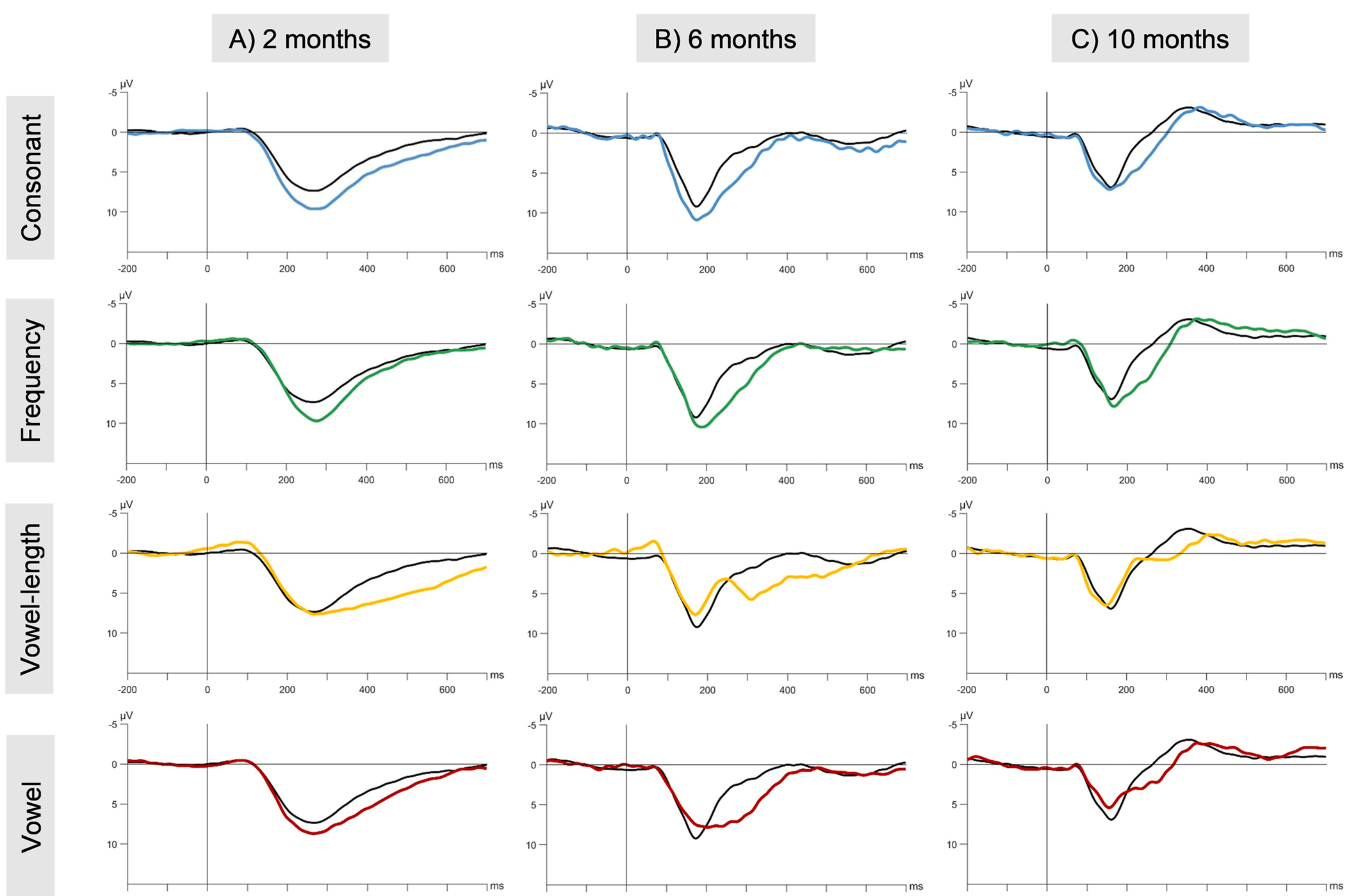

Fig. 1. Illustration of event-related potentials (ERPs) in response to the standard stimulus /ba/ (black) and in response to the four deviant categories [i.e., consonant change /ga/ (blue), frequency change /ba+ / (green), vowel-length change /baa/ (yellow), and vowel change /bu/ (red)] at frontocentral electrodes (FC1, FC2, FC5, FC6). 1A 2-month-olds' ERPs. Illustrated are the ERPs for all 2-month-olds included in the statistical analysis (n = 50). 1B 6-month-olds' ERPs. Illustrated are the ERPs for all 6-month-olds included in the statistical analysis (n = 53). 1C 10-month-olds' ERPs. Illustrated are the ERPs for all 10-month-olds included in the statistical analysis (n = 51). [print in colour].

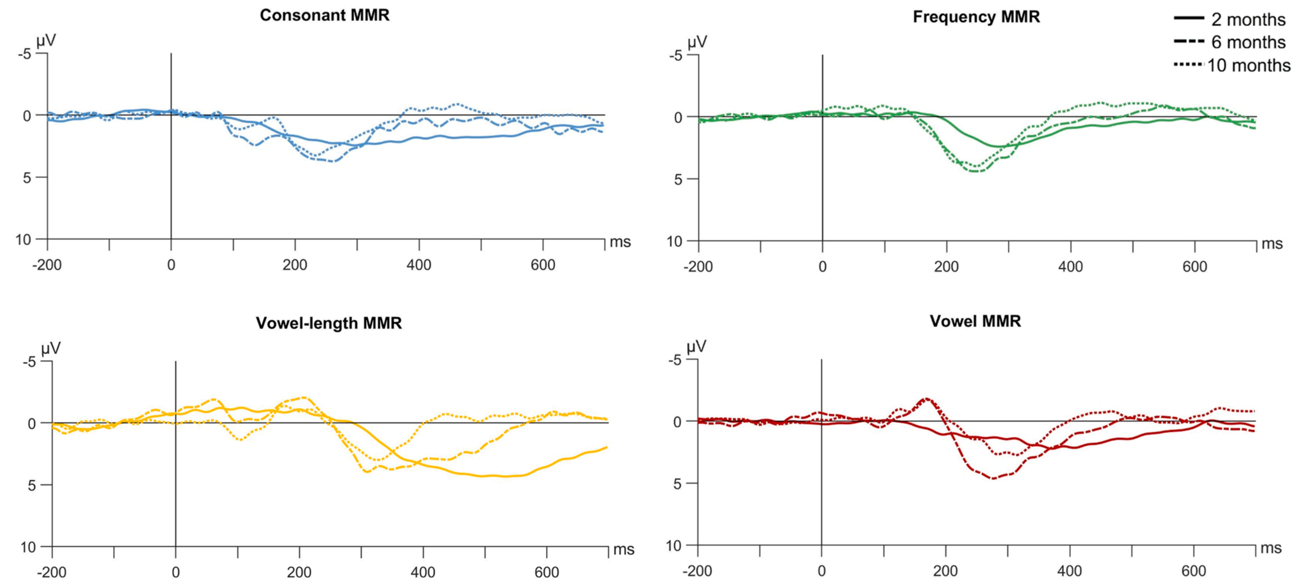

Fig. 2. Illustration of difference waves for the comparison of standard and the four deviants [i.e., consonant change/ga/ (blue), frequency change /ba+ / (green), vowel-length change /baa/ (yellow), and vowel change /bu/ (red)] at frontocentral electrodes (FC1, FC2, FC5, FC6) across assessment points (2, 6, 10 months). [print in colour].

Table 1
Significant positive clusters in the cluster-based permutation analyses, separately for each deviant and assessment point. Only clusters with a length > 100 ms and an MMR-typical, frontocentral distribution, are listed here.

Permutation cluster	Cluster length
Standard vs. *Consonant* ERPs	
2 months	160 – 610 ms ***
6 months	100 – 358 ms ***
10 months	178 – 352 ms ***
Standard vs. *Frequency* ERPs	
2 months	218 – 376 ms **
6 months	176 – 352 ms ***
10 months	162 – 326 ms ***
Standard vs. *Vowel-length* ERPs	
2 months	316 – 698 ms ***
6 months	268 – 532 ms **
10 months	272 – 384 ms **
Standard vs. *Vowel* ERPs	
2 months	226 – 530 ms ***
6 months	214 – 394 ms ***
10 months	218 – 354 ms **

Note. * p < .05; ** p < .01; *** p < .001

(*consonant*) model fit. Only the TLI of the *consonant* model fell slightly under the desired value of.95 (i.e., TLI_{con} =0.94).

The baseline model including the slope fit the data better than the model not including change in the conditions *consonant*, $\Delta\chi\ 2 = 12.22$, $\Delta df = 4$, $p = .016$, *vowel-length*, $\Delta\chi\ 2 = 26.33$, $\Delta df = 4$, $p < .001$, and *vowel*, $\Delta\chi\ 2 = 11.53$, $\Delta df = 4$, $p = .021$. The *frequency* baseline model had a marginally significant better fit than the model not including change, $\Delta\chi\ 2 = 9.16$, $\Delta df = 4$, $p = .057$. Thus, for all four *deviant* types, the MMR amplitude changed (marginally) significantly across the three assessment points (2, 6, 10 months).

Based on the estimations in the baseline models, we fixed the slope-loadings to describe a quadratic trajectory in the *consonant* model, a linear trajectory in the *vowel-length* model and an inverted u-shaped trajectory in the *vowel* model. As the 10-month-MMR's loading on the slope in the *frequency* model did not point towards a "standard" trajectory (i.e., linear, quadratic) in the *frequency* model, we did not fix it to a specific value. Instead, we included a second latent slope factor, with the first slope describing the change in amplitude from 2 to 6 months, and the second slope describing the change in amplitude from 6 to 10 months. All models were non-significant in the chi-square test and fit indices indicated a good (*frequency, vowel-length*, *vowel*) or acceptable (*consonant*) fit to the data. LRTs comparing the fixed slope models (*consonant*, *vowel-length*, *vowel*) with the preceding models yielded no significant difference in model fit for any of the three conditions: *consonant,* $\Delta\chi^2 = 0.03$, $\Delta df = 1$, $p = .862$, *vowel-length*, $\Delta\chi^2 = 0.01$, $\Delta df = 1$, $p = .930$, and *vowel*, $\Delta\chi^2 = 0.9$, $\Delta df = 1$, $p = .769$. Thus, fixing the third slope loading did not impair model fit.

In the following, the final models will be described in more detail. In the *consonant* model (see Fig. 4), the slope loadings were 0 (2 months), 1 (6 months) and 4 (10 months), indicating a quadratic growth curve. The intercept was estimated to be positive (1.89), and the estimated slope value was negative (−0.3). Thus, 2-month-old infants started with a positive MMR in response to *consonant* deviants that decreased towards a negativity from 2 to 10 months in a quadratic trajectory. Covariance of intercept and slope was negative (cov = −2.34).

In the *frequency* model (see Fig. 4), estimations for the intercept (1.83) and the 2–6-month-slope were positive (1.12), while the 6–10-month-slope was estimated to be negative (−0.37), also modelling an inverted u-shape. Thus, the MMR amplitude to *frequency* deviants was positive at 2 months and increased until 6 months, before it declined until 10 months to an amplitude that was less positive than the 6-month-MMR, but more positive than the 2-month-MMR amplitude.

For the *vowel-length* model (see Fig. 4), slope loadings were fixed to 0 (2 months), 1 (6 months) and 2 (10 month), describing a linear trajectory. The estimated intercept value was positive (3.3), while the slope value was estimated to be negative (−1.51). Thus, infants exhibited a positive MMR amplitude in response to the *vowel-length* deviant at 2 months that linearly decreased towards a negativity over time. Intercept and slope covaried negatively (cov = −1.44).

For the *vowel* model (see Fig. 4), we fixed slope loadings to 0 (2 months), 1 (6 months) and − 1 (10 months), modelling an inverted u-shape. Estimated values for the intercept (1.56) and the slope were positive (0.71): Infants exhibited positive MMR amplitudes to the *vowel* deviant at 2 months, which increased between 2 and 6 months and then decreased from 6 to 10 months to a more negative amplitude than was observed at 2 months. There was a small positive covariance between intercept and slope (cov = 0.55).

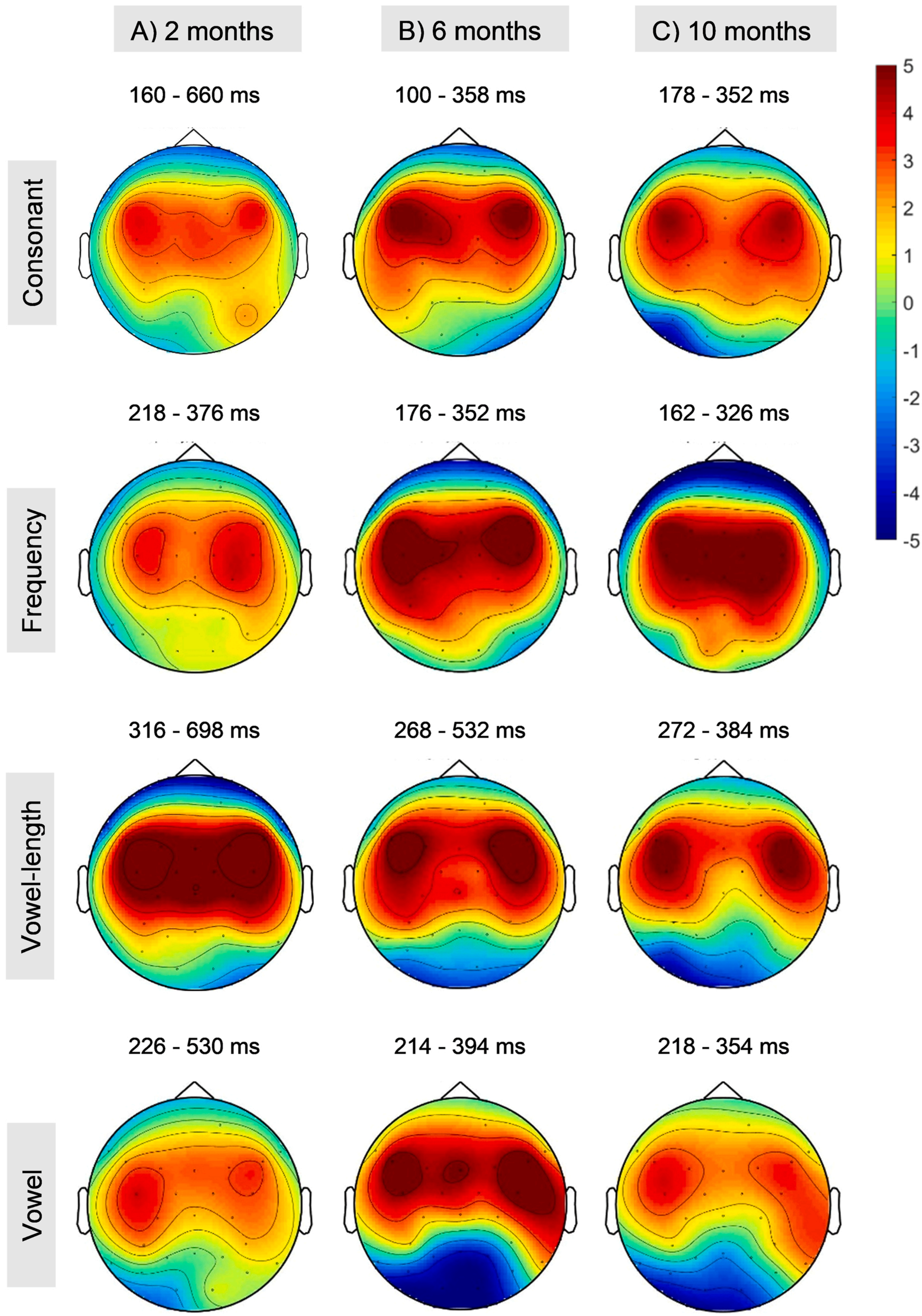

Fig. 3. Topographic representations of *t*-values within the strongest significant cluster for each deviant (consonant, frequency, length, vowel). Depicted are average values within the entire significant cluster. 3A Topographic representations of cluster-based permutation test results at 2 months (n = 50). 3B Topographic representations of cluster-based permutation test results at 6 months (n = 53). 3C Topographic representations of cluster-based permutation test results at 10 months (n = 51).

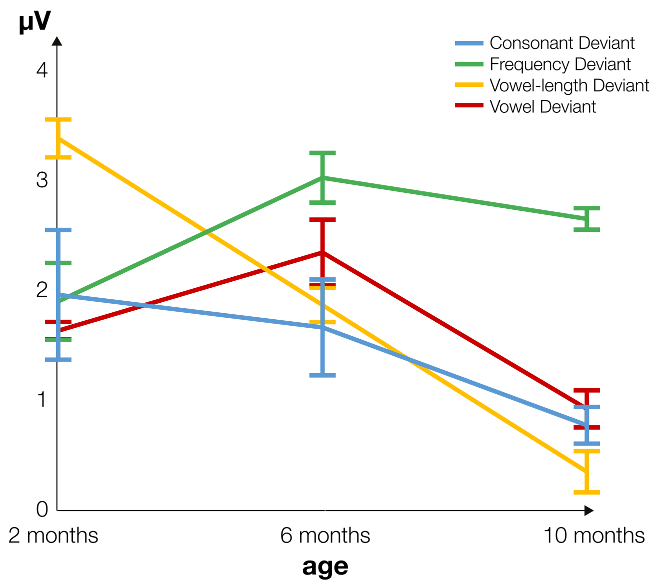

Fig. 4. Illustration of the mean values for the MMR amplitudes in response to the four different speech features (i.e., *consonant*, *frequency*, *vowel-length*, *vowel*) across the different assessment points (i.e., 2, 6 and 10 months) as estimated by the final growth curve models. [print in colour].

4. Discussion

The present study investigated the maturational trajectories of infant discrimination abilities of *consonant*, *vowel-length*, *frequency* and *vowel* contrasts during the first year of life. Discrimination was assessed via the infant MMR at 2, 6 and 10 months in the electrophysiological multi-feature paradigm. We applied separate SGMs to examine the MMRs' amplitude trajectories between 2 and 10 months of age. We observed p-MMRs at all assessment points for all *deviants*, which contradicts our expectations of p-MMRs to be observed only at 2 months, and n-MMRs at later assessment points. However, consistent with our hypotheses, all MMR amplitudes decreased from 2 to 10 months (*consonant, vowel-length*) or from 6 to 10 months (*vowel, frequency*) towards a less positive, i.e., more negative amplitude (see also Cheng et al., 2013; He et al., 2007; Trainor et al., 2003).

Our finding of only p-MMRs in response to all studied contrasts from 2 to 10 months contradicts previous studies (Cheng et al., 2013, 2015; Friedrich et al., 2009; Schaadt et al., 2015). P-MMRs are usually observed when infant auditory discrimination comes with high attentional demands (Cheng et al., 2015; Friederici et al., 2007). As the implementation of the multi-feature paradigm required infants to discriminate four contrasts in parallel instead of only one (i.e., traditional oddball paradigm), our paradigm may have led to higher attentional demands reflected in the prominence of the p-MMR throughout the first ten months of life. However, the decrease in MMR amplitudes seen for all contrasts can be conceived as a decrease in p-MMR towards an n-MMR, since previous studies found the p-MMR and the n-MMR to coexist and co-evolve in infancy (Friederici et al., 2002; Friedrich et al., 2004; He et al., 2007; Leppänen et al., 1997; Trainor et al., 2003). This interpretation is supported by our observation that the duration of permutation clusters decreased across age, possibly indicating the emergence of the n-MMR in later TWs that cancelled out the dominant p-MMR, leading to non-significance in later TWs.

Crucially, the particular shapes of the MMR amplitude trajectories differed between *deviant* types. The *consonant* MMR decreased in a quadratic growth curve, while the *vowel* MMR first increased (i.e., less mature) between 2 and 6 months to then decline from 6 to 10 months. As native-language attunement starts earlier for vowels than for consonants (Best and McRoberts, 2003; Kuhl et al., 1992, 2008; Tsuji and Cristia, 2014; Werker and Lalonde, 1988), we would have expected an earlier maturation (reflected in amplitude decrease) of the *vowel* MMR compared to the *consonant* MMR. In contrast, our results suggest that native-language attunement affects the MMR's maturation non-linearly across development. Especially inverted u-shaped trajectories, as observed for the *vowel* MMR, are discussed to be related to the acquisition of new processing strategies, challenging children's cognitive capacities and impairing their performance until cognitive demands are met and performance recovers to more advanced levels (Siegler, 2004). For native-language attunement it has indeed been proposed that it first requires enhanced attentional processes to establish new perceptual routines for native-contrast discrimination (Jusczyk et al., 1993; Strange, 2011), possibly reflected in the observed initial increase of the *vowel* p-MMR amplitude. Along with native-language attunement, children's cognitive capacities should gradually meet attentional demands, which is most likely reflected in our finding of a more negative *vowel* MMR amplitude at 10 compared to 6 months.

In contrast to the *vowel* MMR amplitude, the *consonant* MMR amplitude did not show an initial increase. As infants attune later to native consonants than native vowels (Best and McRoberts, 2003; Werker and Lalonde, 1988), attentional demands associated with *consonant* discrimination might not (yet) be as high as those associated with *vowel* discrimination between 2 and 6 months. In fact, consonants have been reported to only gain importance for behavioural word recognition from 8 months on (Nishibayashi and Nazzi, 2016; Poltrock and Nazzi, 2015). Thus, it could well be that attentional demands associated with *consonant* discrimination and native-language attunement are not entirely captured by our tested age groups and might only become relevant after the age of 10 months.

Interestingly, we also found different developmental trajectories for the *vowel-identity* and *vowel-length* MMR. While the *vowel-identity* MMR matured in an inverted u-shaped trajectory, the *vowel-length* MMR matured linearly (i.e., became less positive), suggesting differences in native-language attunement and associated attentional processes also for *vowel-identity* vs. *vowel-length* contrasts in German infants (vowel-length is phonemic in German). Importantly, durational aspects of the auditory signal are already fully perceived in the womb, whereas spectral information (relevant for *vowel-identity* discrimination) is only partially available to the fetus (Granier-Deferre et al., 2011; Querleu et al., 1988). Consequently, native-language attunement to *vowel-length* contrasts might start sooner after birth than attunement to *vowel-identity* contrasts and the attentional demands associated with *vowel-length* discrimination may already be highest within the first two months of life, causing the *vowel-length* MMR amplitude to decrease linearly from 2 months on. Supporting this hypothesis, a recent behavioural study in Czech, a language in which vowel-length is also phonemic, found infants to be sensitive to *vowel-length* contrasts earlier than to *vowel-identity* contrasts (Paillereau et al., 2021).

Similar to the *vowel* MMR amplitude, we also found an inverted u-shaped trajectory for the *frequency* MMR. Since a change in frequency mainly becomes apparent in the vowel-part of CV syllables, and frequency perception contributes to the discrimination of different vowel categories (Molis, 2005; Nearey, 1989; Strange, 1989), both perceptual abilities may follow a similar developmental trajectory. Surprisingly, though, the *frequency* MMR only decreased slightly from 6 to 10 months, after increasing (i.e., less mature) from 2 to 6 months, and its amplitude changed only marginally significantly across age. As already fetuses and newborns are able to discriminate different *frequencies* (Alho et al., 1990; Draganova et al., 2005; Háden et al., 2009; Leppänen et al., 1997; Partanen, Kujala et al., 2013; Partanen, Pakarinen et al., 2013; Thiede et al., 2019), we would have expected a strong amplitude decrease between 2 and 10 months. However, the n-MMR component to *frequency* contrasts may have already started to increase at 2 months due to infants' very early sensitivity to pitch. This could imply that the relatively short duration of the *frequency* permutation clusters from 2 months on was partially influenced by an already evolving *frequency* n-MMR in later time windows. Hence, we might have only captured the p-MMR-component of the *frequency* MMR instead of the entire MMR with its p- and n-MMR-components. Future studies should examine the *frequency* MMR's development longitudinally from birth, to provide a fuller picture of its development.

Taken together, while our findings are in line with the general notion of MMR amplitude development from positive to negative polarity, they offer new insights on potential multi-stage developments. Our study was the first to systematically investigate and compare MMR amplitude trajectories to different language-related *contrasts* across the first year of life, while most previous studies were based on single time-point or cross-sectional observations (e.g., Kailaheimo-Lönnqvist et al., 2020; Mueller et al., 2012; Partanen, Kujala et al., 2013). Moreover, the few studies following the MMR development longitudinally did not investigate its featurespecific shape (Cheng et al., 2013, 2015; Pena et al., 2012; Pihko et al., 1999; Weber et al., 2004) and differences in study design and analytic approach might have further caused discrepant results. Our findings, however, highlight the importance of investigating more fine-grained longitudinal trajectories in developmental research. Further, they have important implications for the utilisation of the infant MMR for examining current or predicting later language abilities and potential difficulties. We here show that the longitudinal trajectory of the MMR amplitude might be more informative for language development than single time-point assessments. For example, in our *consonant* and *vowel-length* models, infants with a more positive p-MMR at 2 months tended to show a higher rate of MMR amplitude decrease across time (i.e., negative covariance of intercept and slope). Consequently, p-MMRs at the beginning of life do not necessarily indicate poorer future language abilities (e.g., Gu and Bi, 2020; Männel et al., 2017; Schaadt et al., 2015; Schaadt and Männel, 2019; Thiede et al., 2019; Volkmer and Schulte-Körne, 2018), but might be associated with a higher maturational rate across the first year of life. A similar idea has been put forward by García-Sierra et al. (2021), who argued that early enhanced p-MMR amplitudes to native-language contrasts may facilitate the subsequent attunement to these contrast, which would be indicated by a stronger development towards n-MMRs. We thus argue that the longitudinal trajectory of MMR amplitude change might be a more accurate and useful predictor of later language abilities than isolated MMR assessments.

4.1. Limitations and implications for future research

We may highlight that the MMR's amplitude and polarity is not only affected by age and language abilities, but also by choice of the studied contrast (Cheng et al., 2015; Sambeth et al., 2009), language background (Cheng et al., 2015; Friedrich et al., 2009; Kuhl et al., 2008; Lee et al., 2012) and study-design features (Ahmmed et al., 2008; Cheng et al., 2013; Leppänen et al., 1999). Consequently, conclusions drawn from our study are limited to the four studied contrasts (*consonant*, *vowel-length*, *frequency*, *vowel*) in German-learning infants, using our specific study-design (e.g., multi-feature design, ISI). For our results to be generalised to other experimental frameworks and language backgrounds, more studies examining the infant MMR's maturation are needed.

In addition, investigating the MMR's development before 2 months and beyond 10 months of age will provide further information on the developmental time course of the MMR amplitude to different contrasts. Given that three assessment points are the minimum number required for investigating non-linear growth curves (Byrne and Crombie, 2003; Curran et al., 2010; Duncan and Duncan, 2009), including more assessments across a longer period of time will add important insights into the developmental progression of discrimination abilities beyond the first year of life.

5. Conclusion

In conclusion, we found p-MMRs in response to *consonant*, *frequency*, *vowel-length* and *vowel* contrasts across the first year of life that decreased towards a negativity with increasing age. Importantly, the maturational trajectory of the MMR amplitude decline differed depending on the studied contrast. Here, our study takes a first step in showing that compelling insights into developmental processes can be gained from focusing on longitudinal trajectories of speech discrimination. Such research not only deepens our understanding of the development of speech perception, but also offers ways of utilising both single time-point assessments as well as longitudinal trajectories as predictors of developmental outcomes (e.g., language problems).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2022.101127.

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