DOI: 10.1111/cdev.13892

EMPIRICAL ARTICLE

CHILD DEVELOPMENT

# Maturation of consonant perception, but not vowel perception, predicts lexical skills at 12 months

**Gesa Schaadt**[1,2] | **Annika Werwach**[3,4] | **Hellmuth Obrig**[3,5] | **Angela D. Friederici**[2] | **Claudia Männel**[2,3,6]

[1]Department of Education and Psychology, Freie Universität Berlin, Berlin, Germany
[2]Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
[3]Clinic for Cognitive Neurology, Medical Faculty, University Leipzig, Leipzig, Germany
[4]Max Planck School of Cognition, Leipzig, Germany
[5]Department of Neurology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
[6]Department of Audiology and Phoniatrics, Charité–Universitätsmedizin Berlin, Berlin, Germany

**Correspondence**
Gesa Schaadt, Department of Education and Psychology, Freie Universität Berlin, Fabeckstraße 35, 14195 Berlin, Germany.
Email: gesa.schaadt@fu-berlin.de

**Funding information**
Deutsche Forschungsgemeinschaft, Grant/Award Number: MA 6897/2-1

**Abstract**

Consonants and vowels differentially contribute to lexical acquisition. From 8 months on, infants' preferential reliance on consonants has been shown to predict their lexical outcome. Here, the predictive value of German-learning infants' ($n = 58$, 29 girls, 29 boys) trajectories of consonant and vowel perception, indicated by the electrophysiological mismatch response, across 2, 6, and 10 months for later lexical acquisition was studied. The consonant-perception trajectory from 2 to 6 months ($\beta = -2.95$) and 6 to 10 months ($\beta = -.91$), but not the vowel-perception trajectory, significantly predicted receptive vocabulary at 12 months. These results reveal an earlier predictive value of consonant perception for word learning than previously found, and a particular role of the longitudinal maturation of this skill in lexical acquisition.

Foundations of language development are already established before birth (e.g., Draganova et al., 2005), followed by important language milestones during the first year of life. Already newborns show remarkable perceptual capacities in the linguistic domain (Dehaene-Lambertz & Spelke, 2015; Friederici, 2006; Perani et al., 2011), including the ability to discriminate speech sounds (Dehaene-Lambertz & Pena, 2001; Partanen et al., 2013). These phonological abilities rapidly advance throughout the first year of life, with infants starting to acquire native-language phonetic categories from the age of 6 months (Kuhl, 2004; Kuhl et al., 2005; Polka & Werker, 1994). The development of phonological abilities is a crucial acquisition step of the language development process, as phonological processing bootstraps lexical acquisition (see Johnson, 2016; Kuhl et al., 2008; Werker & Yeung, 2005). Here, consonant and vowel perception might play differential roles for the development of lexical processing. According to the distribution of labor theory (Hochmann et al., 2011), vowels primarily

---

**Abbreviations:** CFI, comparative fit index; EEG, electroencephalography; ELFRA, Elternfragebögen für die Früherkennung von Risikokindern; ERP, event-related potential; ICA, independent component analysis; LGM, latent growth curve model; MMN, mismatch negativity; MMR, mismatch response; n-MMR, negative MMR; p-MMR, positive MMR; RMSEA, root mean square error of approximation; SGM, second-order growth curve model; TLI, Tucker Lewis index; TW, time window.

Gesa Schaadt and Annika Werwach contributed equally.

contribute syntactic processing, whereas consonants most reliably inform about word identity. It is argued that, in many languages, consonants carry more information about the lexicon due to their higher quantity and stronger distinctiveness in a lexical context compared to vowels (Nespor et al., 2003). In adult lexical processing, speakers across many languages are biased towards consonantal information in lexical tasks (for an overview, see Nazzi & Cutler, 2019), although there seem to be some exceptions depending on the relative importance of vowels and consonants in the respective language (Gómez et al., 2018; Poltrock et al., 2018; Wiener & Turnbull, 2016). Importantly, this stronger reliance on consonants in lexical processing, also termed consonant bias, is not yet found in young infants, who instead show a lexical vowel bias (Benavides-Varela et al., 2012; Nazzi & Cutler, 2019 for an overview). This suggests a developmental transition from a vowel- to a consonant bias, which has been demonstrated for Italian-, French-, Spanish-, and English-learning infants during their first years of life (Bouchon et al., 2015, 2022; Hochmann et al., 2018; Nazzi et al., 2009; Nishibayashi & Nazzi, 2016; Von Holzen & Nazzi, 2020). However, this development seems to depend on an interaction between age and the specific characteristics of the respective language, with no consonant bias being found in Danish-, Cantonese- or Mandarin-learning infants (Chen et al., 2021; Hojen & Nazzi, 2016; Singh et al., 2015; Wewalaarachchi & Singh, 2020). The proposed prerequisites for the transition from an initial vowel- to a lexical consonant bias differ across theoretical accounts: While the lexical hypothesis (Keidel et al., 2007) leaves phonological processing aside, stressing the relevance of knowledge about the lexicon's structure, the acoustic-phonetic (Floccia et al., 2014; Hochmann et al., 2011; Nespor et al., 2003) and the hybrid phono-lexical account (Nishibayashi & Nazzi, 2016; Poltrock & Nazzi, 2015) both emphasize the importance of phonological development for the emergence of the consonant bias, focusing on the acquisition of native-language phonetic categories. The acoustic-phonetic hypothesis (Floccia et al., 2014; Hochmann et al., 2011; Nespor et al., 2003) argues that infants initially rely on salient acoustic properties like vowels, but as infants' phonological development advances, they learn that consonant categories are acoustically more distinct than vowel categories, rendering consonants more reliable cues to word identity (Floccia et al., 2014). The phono-lexical hypothesis combines these two approaches, proposing that both acoustic-phonetic and lexical information interact and contribute to the development of the consonant bias (Nishibayashi & Nazzi, 2016; Poltrock & Nazzi, 2015). Therefore, according to the latter two hypotheses, the development of phonological processing and the acquisition of phonetic categories constitute important prerequisites for the emergence of the consonant bias and thus for lexical processing.

Two previous studies with French-learning infants addressed the predictive value of infants' reliance on consonants versus vowels in word recognition for later vocabulary. The first study found electrophysiological responses to both consonant and vowel changes in lexical contexts at 8 months to predict later vocabulary growth (Von Holzen et al., 2018). On the contrary, Von Holzen and Nazzi (2020) reported a behavioral vowel bias at the age of 11 months to positively predict productive vocabulary growth, and a consonant bias to even be related to smaller growth in productive vocabulary across the second year of life. While these two studies investigated infants' processing of consonants and vowels at the lexical level, consonant and vowel perception per se might also be predictive of infants' later lexical acquisition. Both the acoustic-phonetic hypothesis and the phono-lexical account emphasize the importance of consonant and vowel perception and the acquisition of native-language phonetic categories for the development of a consonant bias in lexical processing (see Bonatti et al., 2007; Floccia et al., 2014; Poltrock & Nazzi, 2015). Consequently, the development of infants' early vowel and consonant perception may already be associated with later lexical acquisition. Thus, the longitudinal trajectories of consonant and vowel perception should be evaluated in association with later lexical acquisition over and above single time-point (cross-sectional) consonant and vowel perception.

To measure consonant and vowel perception in young infants, the event-related potential (ERP) mismatch negativity (MMN) can be used (Näätänen & Alho, 1997; Näätänen et al., 2007). The MMN is typically tested with a passive-listening oddball paradigm (Squires et al., 1975), in which a repetitive standard stimulus is occasionally replaced by a deviant stimulus; and has a good test–retest reliability in adults (Tervaniemi et al., 1999; Wang et al., 2021). The difference value between the standard-stimulus ERP and the deviant-stimulus ERP indicates the perception of a violation of an established prediction (i.e., mismatch response; MMR). While the adult MMR is typically observed to be negative in polarity (for reviews, see Näätänen & Alho, 1997; Näätänen et al., 2007), positive MMRs (p-MMR) are often reported for newborns and infants (e.g., He et al., 2009; Mueller et al., 2012). Importantly, an MMR is elicited without an individual's attention (e.g., Alho et al., 1994; Näätänen et al., 1993) and even during infant sleep (e.g., Cheour et al., 2000; Friedrich et al., 2004). This underlines its suitability for assessing auditory and speech perception, including consonant and vowel perception, already in very young infants.

Infant MMRs can occur as two or three distinct components, a positive and one or two negative deflection(s) with varying latencies (Friederici et al., 2002; Friedrich et al., 2004; He et al., 2007; Kushnerenko et al., 2002; Leppänen et al., 1997) developing at different time scales. 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 negative MMR (n-MMR) to speech sounds may be related to the acquisition of native-language phonetic categories (Friedrich et al., 2009; Garcia-Sierra et al., 2016; Rivera-Gaxiola et al., 2005). As a result, the MMR in infants shows a developmental shift from positivity to negativity (Cheng et al., 2013; He et al., 2007; Kushnerenko et al., 2002; Trainor et al., 2003), which is indicative of advancing language development, if measured in response to speech sounds (e.g., Garcia-Sierra et al., 2016; Kuhl & Rivera-Gaxiola, 2008). Since infants usually show a p-MMR at the beginning of life (Cheng et al., 2013; Dehaene-Lambertz & Pena, 2001; He et al., 2009), we operationalized the decrease of the p-MMR-component (towards an n-MMR) as a measure of maturation in this study.

Due to its suitability for assessing auditory and speech processing in infancy, the MMR has been used for predicting infants' later lexical development. For example, Friedrich et al. (2009) could show that the MMR's characteristic of 5-month-olds can predict their lexical skills at age 24 months. However, up to now the developmental trajectory of consonant and vowel perception across the first year of life has not been considered in terms of their predictive value for infants' later lexical skills. Thus, the present study investigated the developmental trajectory of German-learning infants' consonant and vowel perception across the first year of life (i.e., at 2, 6 and 10 months) by means of the infant MMR to find out how the maturational slopes and single time-point measurements of consonant and vowel perception predict productive, as well as receptive vocabulary at 12 months. To directly compare the perception of consonants and vowels, the MMR to both speech features was measured within one session in a multifeature paradigm (Näätänen et al., 2004) longitudinally when infants were 2, 6, and 10 months old. To explore how the maturation of consonant and vowel perception relates to later lexical skills, we assessed productive and receptive vocabulary when infants were 12 months old using the German version (Elternfragebögen für die Früherkennung von Risikokindern, ELFRA; Grimm & Doil, 2000) of the parental questionnaire MacArthur-Bates Communicative Development Inventories (Fenson, 2002). Second-order latent growth curve model (LGM) analysis was used to assess the maturational trajectory of the infant MMR to consonants and vowels across the first year of life. Estimated values for the individual maturational slope and intercept were then entered into multiple regression models, predicting infants' later productive and receptive vocabulary at 12 months.

We hypothesized the longitudinal development of electrophysiological indicators of either consonant- or vowel perception, or a combination of both, to be related to later lexical acquisition. This may manifest in three scenarios: (1) Only the development of phonetic consonant categories (indicated by more mature, that is, negative, MMRs to consonant contrasts) facilitates lexical acquisition via an early emergence of the consonant bias, with the development of vowel perception being unrelated to this process. (2) Since a behavioral vowel bias in lexical processing was still observed in 9-month-old German-learning infants (Schmandt et al., 2022), early vowel perception may relate to infants' later lexical acquisition, with consonant perception coming into play at a later age (e.g., in the second half of the first year of life). (3) Infants first need to construct phonetic categories for both consonants and vowels to recognize the advantage of consonants compared to vowels in lexical processing and acquisition. This would predict that more mature electrophysiological responses (i.e., more negative MMRs) to both vowel and consonant contrasts correlate with later lexical acquisition. Since our study is the first to consider the longitudinal development of consonant and vowel perception in relation to lexical acquisition, it is primarily explorative.

# MATERIALS AND METHODS

## Participants

Infants were recruited from the Infant Database of the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig, Germany. For our longitudinal study, 75 infants and their parents were invited to participate at the ages of 2, 6, 10 and 12 months between October 2017 and March 2020. To enter the analyses, at least two electroencephalography (EEG) datasets of sufficient quality (i.e., a minimum 400 artifact-free trials, i.e., 50%) had to be available per infant from all three EEG assessments (2, 6 and 10 months). Datasets of 16 infants did not reach this criterion and were thus excluded from further analysis. One additional dataset was excluded due to the infant's poor eyesight, as visual impairments have been shown to impact language development (e.g., Mosca et al., 2015). Thus, the final sample was $n = 58$ (29 girls, 29 boys). When infants were 12 months old, parents filled in language questionnaires for 40 of these 58 infants. Mean ($M$) age of infants was 2.28 months at the first (standard deviation [SD] = 0.26 months), 6.71 months (SD = 0.32 months) at the second, 10.54 months (SD = 0.27 months) at the third, and 12.03 (SD = 1.29) at the fourth assessment. All infants were born full-term (gestation week 37 or later, $M$ = 39 weeks, SD = 1.37 weeks) with normal birth weight (above 2500 g, $M$ = 3554.87 g, SD = 383.82 g) and without any diagnosed hearing deficits or neurological problems (parental report). All infants were from White, monolingual German families with predominantly mid to high socioeconomic backgrounds. Twenty-nine percent of mothers and 46.3%

of fathers had completed vocational training, and 65.5% of mothers and 51.9% of fathers had a university degree (or higher) or were currently in the process of gaining one.

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).

## Protocol

The same EEG experiment was conducted for each infant when they were 2, 6, and 10 months old. Experiments were carried out in a silent, child-friendly room. Parents received written and oral information about the study's aim and procedure and provided written informed parental consent. Subsequently, infants were prepared for the EEG recordings. During the experiment (duration: 13 min), infants lay (age 2 months) or sat (age 6 and 10 months) on their parent's lap and were, if necessary, entertained using silent toys or fed by their parents. The number of infants who were fed during EEG data collection was $n = 6$ at 2 months, $n = 3$ at 6 months, and $n = 2$ at 10 months. Trials including artifacts that resulted from feeding, heavy movement, crying, or vocalizing were excluded from further analysis (see EEG recordings and analysis). As previous studies demonstrated a reliable elicitation of the MMR in various infant sleep states (e.g., Cheour et al., 2000; Friedrich et al., 2004), infants were not prevented from falling asleep during the experiment. The number of infants whose datasets were included in this study and who slept during the experiment, as indicated by closed eyes during the majority of the experiment or alpha waves and/or sleep spindles in the EEG signal, was $n = 8$ at 2 months, $n = 0$ at 6 months, and $n = 2$ at 10 months.

The entire procedure lasted for about 60 min. Parents were reimbursed for their travel expenses by 7.50 € and could pick a toy for their infants. One week before the child's first birthday, parents were sent the language questionnaire (ELFRA; Grimm & Doil, 2000) together with a prepaid envelope.

## Infant speech perception

### *Paradigm and stimuli*

For the assessment of infant speech perception abilities, we applied a multifeature paradigm with semisynthesized syllables as stimuli at all three EEG assessments. This paradigm allows for the simultaneous presentation of multiple speech-deviants within one experiment. It has yielded comparable results to the traditional oddball paradigm in studies with infants (Partanen et al., 2013), school children (Lovio et al., 2009), and adults (Pakarinen et al., 2009).

The syllable /ba/ was the *standard* stimulus. As deviant stimuli, four different syllables were selected, based on previous research studying MMRs in infants at the age of 2 months or younger (Cheng et al., 2015; Friedrich et al., 2004; Mahmoudzadeh et al., 2013; Partanen et al., 2013). Specifically, the syllable /ga/ was used as the *consonant* deviant (Cheng et al., 2015; Mahmoudzadeh et al., 2013) and the syllable /bu/ (Cheng et al., 2015; Koerner et al., 2016) as the *vowel* deviant. Two additional deviant syllables were included as part of another study (Werwach et al., 2022), namely the *frequency* deviant /ba+/, for which pitch was raised by +16 Hz (Partanen et al., 2013) and the *vowel-length* deviant /ba:/, for which the vowel /a/ was lengthened by 100 ms (Friedrich et al., 2004). Stimuli were recorded by a female native German speaker (16-bit sampling rate, 44.1 kHz digitization) and then adjusted using Praat Version 6.0.28 (Boersma, 2001). Each stimulus length was set to 170 ms (except for the *length* deviant /ba:/, set to 270 ms) and a silent period of 50 ms was added before each syllable onset and after offset. All stimuli were set to the same intensity by extracting the intensity tire of the *standard* stimulus /ba/ and multiplying it with the other stimuli. Consequently, the *deviant* stimuli (i.e., /ga/, /ba+/, /ba:/, /bu/) had the same intensity as the *standard* stimulus /ba/. All stimuli were normalized to an average intensity of 70 dB Sound Pressure Level (dB). F0 of all stimuli was set to 198 Hz (i.e., the mean pitch of the female German native speaker across all recorded stimuli). Thus, stimuli did not differ in F0 except for the *frequency* deviant /ba+/, for which we increased F0 by 16 Hz, resulting in F0 of 214 Hz. See Table 1 for acoustic parameters of stimuli.

**TABLE 1** Information on acoustic parameters of the standard syllable and deviant syllables

| Acoustic parameters | Standard /ba/ | Deviant /ga/ | Deviant /bu/ | Deviant /ba:/[a] | Deviant /ba+/[a] |
|---|---|---|---|---|---|
| F0 | 198.00 | 198.00 | 198.00 | 198.00 | 214.00 |
| 1st Formant (Hz) | 1145.53 | 918.24 | 350.33 | 1100.41 | 1145.53 |
| 2nd Formant (Hz) | 1497.10 | 1814.13 | 1264.55 | 1499.30 | 1497.10 |
| 3rd Formant (Hz) | 3032.04 | 3039.53 | 3030.41 | 3036.44 | 3032.04 |
| 4th Formant (Hz) | 4217.78 | 4215.47 | 4188.21 | 4212.64 | 4217.78 |

[a] The deviants /ba:/ and /ba+/ were not focused on in the present manuscript.

A total of 800 stimuli were presented via loudspeakers using Presentation® software version 17.2 (Neurobehavioral Systems Inc., 2014). The *standard* syllable and one of the *deviant* syllables were presented in alternation with an interstimulus-interval (ISI, offset to onset) of 800 ms (including the silent period of 50 ms before and after each syllable), a time range used in previous infant MMR studies (e.g., Cheour-Luthanen et al., 1995; Labonte-Lemoyne et al., 2017). Accordingly, the probability of the *standard* syllable was 50% (i.e., 400 standard syllables in total) and each *deviant* syllable had a probability of 12.5% (i.e., 100 syllables per deviant type in total). Presentation order of *deviant* syllables was pseudo-randomized, with the restriction that no more than two *deviant* stimuli of the same kind appeared consecutively. As we were specifically interested in consonant and vowel perception in relation to productive and receptive language development, we will only focus on the MMR amplitude in response to *consonant* and *vowel* deviants for subsequent analyses.

### *EEG recordings and analysis*

The EEG was recorded from 21 Ag/AgCl active electrodes attached to an elastic cap (ActiCap system; Brain Products) at standard positions according to the 10–20 system. Electrooculograms were recorded from electrodes at the outer canthi of both eyes (F9, F10) 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), digitized online at 500 Hz, and recorded using BrainVision Recorder version 1.21.01.02 (Brain Products).

EEG data was processed using the EEGLAB® toolbox (Delorme & Makeig, 2004) and MATLAB® version R2020a (The Math Works Inc., 2020). Offline, EEG data were algebraically re-referenced from CZ to the average of both mastoids. Data were band-pass filtered using a windowed sinc FIR filter (band-pass 1–30 Hz, Kaiser window, $\beta$ = 7.857; filter order = 1208) to remove slow drifts and severe muscle artifacts. Subsequently, the continuous EEG was scanned semiautomatically to identify segments with artifacts (abnormal values above ±100 µV and abnormal trends above a maximum slope of 100 µV per epoch and $R^2$ limit of 0.5). The marked segments containing artifacts were visually scanned to prepare the dataset for the independent component analysis (ICA) and further trials with severe artifacts were manually marked and removed, followed by the actual ICA (Makeig et al., 1996). Resulting ICA components were visually scanned and, based on component topography and waveform, artifact-related components were determined and saved. Re-referenced continuous data was again band-pass filtered at 0.5–30 Hz (windowed sinc FIR filter, Kaiser window, $\beta$ = 7.857; filter order = 824), a band-pass filter setting typically used for analyzing MMRs (e.g., He et al., 2009; Männel et al., 2017; Schaadt et al., 2015). The determined ICA components were applied to the 0.5–30 Hz-filtered dataset and used for data correction. EEG epochs of 700 ms postsyllable onset with a prestimulus baseline of 200 ms were extracted and automatically scanned for artifacts. Epochs with a signal range exceeding 150 µV and abnormal trends above a maximum slope of 150 µV and $R^2$ limit of .5 were rejected from further analysis. Descriptive statistics on the number of included trials per condition (*standard*, *consonant deviant*, and *vowel deviant*) for datasets included in further analysis (more than 50% artifact-free trials in total) can be found in Table S.1. Finally, individual averages for each *deviant* stimulus and for the *standard* stimulus were calculated and grand averages were computed.

## Productive and receptive vocabulary

For the assessment of children's productive and receptive vocabulary, parents completed the German version (ELFRA-1; Grimm & Doil, 2000) of the MacArthur-Bates Communicative Development Inventories (Fenson, 2002) 1 year after birth. This questionnaire comprises scales on speech production, speech perception, gestures, and fine motor skills. For the purpose of our study, we focused on the speech production (Cronbach's $\alpha$ = .84) and speech perception scales (Cronbach's $\alpha$ = .96).

## **Statistical analysis**

Statistical analyses were performed using MATLAB® version R2020a (The Math Works Inc., 2020) and the FieldTrip® toolbox (Oostenveld et al., 2011), as well as R-Studio version 3.6.3 (R Core Team, 2020) and "mvn" package (Korkmaz et al., 2014) for assessment of multivariate normality and multivariate outliers and "lavaan" (Rosseel, 2012) for latent growth curve modeling.

To identify relevant time windows (TWs) and electrode clusters where standard and deviant ERPs significantly differed, nonparametric cluster-based permutation tests (Maris & Oostenveld, 2007, $p < .05$, $\alpha$ = .05, 1000 permutations, ≥2 channels minimum cluster size) were performed for each deviant and assessment point separately. All electrodes except T7 and T8 and all time points between 100–700 ms were included, as the infant MMR to syllable stimuli usually has a latency >100 ms (e.g., Cheng et al., 2015; Dehaene-Lambertz & Dehaene, 1994; Garcia-Sierra et al., 2016). Note that clusters were only considered if they started 100 ms after the onset of auditory deviation between the standard and *deviant* stimulus. For the *consonant* deviant, deviation started with stimulus onset, while for the *vowel* deviant, deviation started 30 ms after stimulus onset. Thus, for the *vowel* contrast, significant clusters were only considered if they started 130 ms after stimulus onset or later. Sample size was $n = 50$ at t1, $n = 53$ at t2 and $n = 51$ at t3. Based on the cluster-based permutation test results, three TWs were chosen per deviant and assessment point to be included in the subsequent second-order growth curve models (SGMs). Multiple TWs were included per assessment point and condition instead of peak amplitudes or mean amplitudes because the infant MMR usually has an extended latency (Cheng et al., 2015; Friedrich et al., 2004; He et al., 2009; Morr et al., 2002; Trainor et al., 2003) and MMR peak latencies shift across age (e.g., Morr et al., 2002; Shafer et al., 2010). Consequently, the peak or mean amplitude of the MMR would not precisely capture the MMR's longitudinal changes since different sections of the MMR may be more or less relevant for the calculation of the MMR across development. SGMs can account for the respective TWs' differential MMR amplitude-weight across test ages by allowing TW's loadings on the latent MMR variable (i.e., the contribution of each TW to the calculation of the MMR) to differ between assessment points. Further, since infants' p-MMRs are typically expressed in long deflections (Dehaene-Lambertz, 2000; Friedrich et al., 2004; He et al., 2007), we considered three TWs to sufficiently capture the duration of the p-MMR and its developmental changes. TWs were chosen according to the following procedure: (1) The longest significant cluster (either at 2, 6, or 10 months) was identified for both *deviants* separately. By this, we accounted for differences in the MMR's duration across *deviants*. (2) The duration of the identified cluster was divided by 3, yielding the length of each of the 3 consecutive TWs included in the SGM for this *deviant*. (3) The first TW was aligned with the cluster onset for each assessment point, to account for potential developmental latency shifts across assessment points. (4) One electrode cluster was chosen for the growth curve analysis, comprising neighboring electrodes with the strongest activation in the cluster-based permutation analyses across both *deviants* and assessment points. This cluster was identical for both deviant conditions and for all TWs.

Then, second-order latent growth curve model analysis was performed to examine the specific maturational trajectory of the MMR in response to the *consonant* and *vowel* deviants between 2, 6 and 10 months. LGMs estimate both the fixed (population values) and random effects (population variance) of the starting point (intercept, e.g., infant MMR amplitude at 2 months) as well as the change over time (slope, e.g., difference in MMR amplitudes between two assessment points) of the variables of interest (Curran et al., 2010; Duncan & Duncan, 2009). The difference between ERPs to the respective *deviant* syllable and the *standard* syllable in the chosen TWs and electrode cluster (i.e., deviant-minus-standard difference waveforms) served as manifest indicator variables (i.e., three manifest variables per assessment point per condition) in two separate models. Based on these manifest indicator variables, the first-order latent variable MMR amplitude was calculated for each assessment point. We first specified a baseline SGM for each *deviant* type with infant MMRs at the three assessment points (2, 6 and 10 months) as first-order latent variables and intercept (i.e., starting point of latent variable MMR amplitude development) and slope (i.e., change in latent variable MMR amplitude over time) as second-order latent 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). However, the loading of the latent 10-month MMR variable on the slope was allowed to be freely estimated to exploratively examine the specific growth trajectory over time (e.g., linear or quadratic). 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. In order to examine whether MMR amplitudes to the two *deviant* types changed over time, likelihood ratio tests (see Gonzalez & Griffin, 2001) using the Satorra–Bentler scaled chi-squared statistic (Satorra & Bentler, 2001) were performed.

For model estimation, we used maximum likelihood estimation and effect coding for scaling (Jeon & Kim, 2020; Little et al., 2006). Under the assumption that data was missing at random, full-information maximum likelihood estimation for missing data was applied. In this way, all available information ($n = 58$) was utilized for model estimation.

Models were considered to fit the data if the chi-squared test was nonsignificant ($p > .05$). In addition, goodness-of fit was evaluated against thresholds recommended by Hooper et al. (2008) and Werner et al. (2016). Model fit was regarded good if the root mean square error of approximation (RMSEA) was ≤.06 and acceptable if RMSEA was ≤.08. In addition, we calculated two incremental fit indices, the comparative fit index (CFI) and the Tucker Lewis index (TLI), that compare the chi-squared value of the tested model to a baseline model. A CFI ≥.95 and a TLI ≥.95 indicate good model fit.

After the SGM analysis, we extracted individual estimated values for the intercept and slope and entered them into multiple regression models as predictors of productive and receptive vocabulary at 12 months, separately for *consonant* and *vowel* MMRs. Sample size for this analysis was $n = 40$.

# RESULTS

## Infant speech perception

Figures 1a–c illustrate the ERPs to standard and deviants, respectively, at ages 2, 6 and 10 months.

Only positive clusters are reported here, since we focused on the developmental changes of the p-MMR,

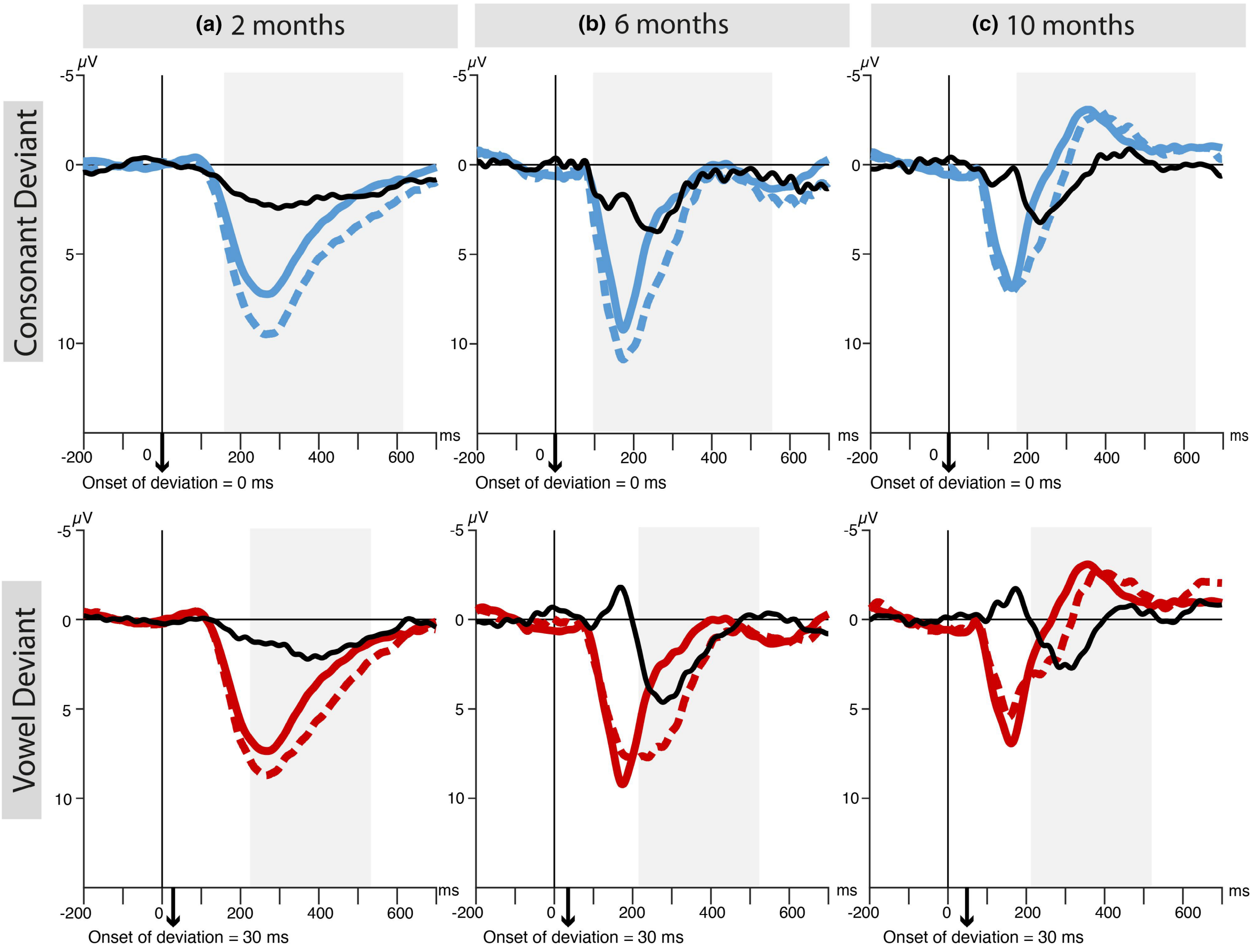

**FIGURE 1** Illustration of event-related potentials in response to the standard stimulus and in response to the consonant and vowel deviants as well as difference waves (deviant—standard). This figure illustrates the event-related potentials (ERPs) in response to the standard stimulus /ba/ (blue and red, solid lines) and in response to the *consonant* (blue, dotted lines) and *vowel* deviants (red, dotted lines) at frontocentral electrodes (FC1, FC2, FC5, FC6). Black lines represent the consonant-standard and vowel-standard difference waves (i.e., deviant—standard). The TWs included in the growth curve analysis are highlighted in gray. Arrows indicate the onset of deviation from the standard syllable. (a) Two-month-olds' ERPs and difference waves. Illustrated are the ERPs for all 2-month-olds included in the statistical analysis ($n = 50$). (b) Six-month-olds' ERPs and difference waves. Illustrated are the ERPs for all 6-month-olds included in the statistical analysis ($n = 53$). (c) Ten-month-olds' ERPs and difference waves. Illustrated are the ERPs for all 10-month-olds included in the statistical analysis ($n = 51$).

which was already present at 2 months. For additional significant clusters, see Supporting Information (S.2). Note that additional significant clusters were either not frontocentrally distributed or started before 100 ms after deviation onset and were thus not considered as indicative of the infant MMR.

For the comparison of standard and *consonant* ERPs, a significant, frontocentrally distributed positive cluster, indicating significant *consonant* MMR amplitudes, was found between 160–610 ms ($p < .001$) at 2 months, between 100–358 ms ($p < .001$) at 6 months and 178–352 ms ($p < .001$) at 10 months. For the comparison of standard and *vowel* ERPs, we found a significant, frontocentrally distributed positive cluster, indicating significant *vowel*-MMR amplitudes, from 226 to 530 ms ($p < .001$) at 2 months, from 214 to 394 ms ($p < .001$) at 6 months and from 218 to 354 ms ($p = .004$) at 10 months. Figures 2a–c show topographical representations of average *t*-values in the respective clusters.

## Longitudinal development of infant speech perception

Based on the results of the cluster-based permutation analysis, we chose frontocentral electrodes (FC1, FC5, FC2, FC6), and three TWs, separately for *consonant* and *vowel* deviants, to be included in subsequent analyses. The longest cluster was found at 2 months for both contrasts. In the *consonant* condition, the cluster was 450 ms. Thus, the three TWs that we included for subsequent SGMs were 150 ms each. In the *vowel* condition, the cluster was 304 ms. Thus, the three TWs that were included for subsequent SGMs were 100 ms. The specific TWs that were used for MMR

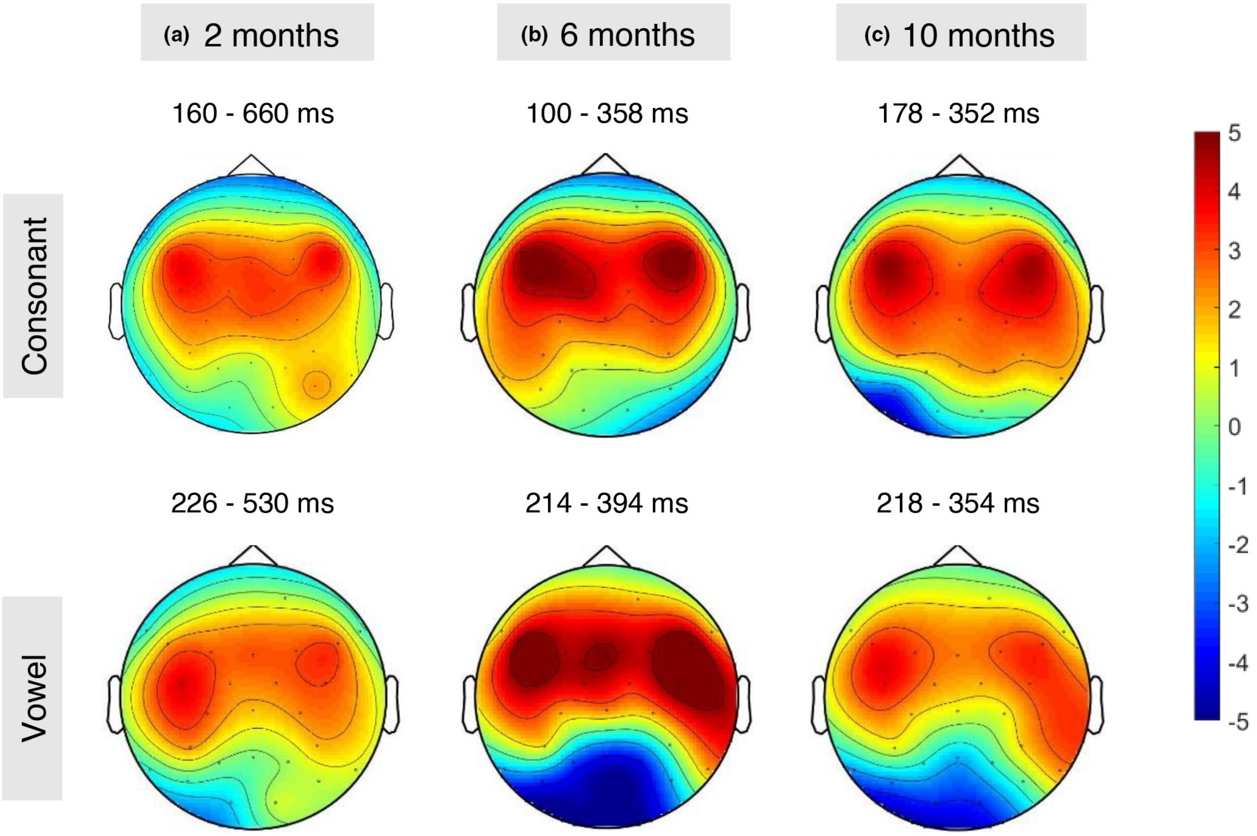

**FIGURE 2** Topographic representations of significant clusters for consonant and vowel contrasts. Illustrated are the topographic representations of *t*-values within the strongest significant cluster for both contrasts (*consonant*, *vowel*). Depicted are average values within the entire significant cluster. (a) Topographic representations of cluster-based permutation test results at 2 months ($n = 50$). (b) Topographic representations of cluster-based permutation test results at 6 months ($n = 53$). (c) Topographic representations of cluster-based permutation test results at 10 months ($n = 51$).

amplitude calculation in the following SGMs are listed in Table S.3.

Mardia skewness and kurtosis and Henze-Zirkler's tests (Henze & Zirkler, 1990; Mardia, 1980) indicated a violation of the multivariate normality assumption in the *vowel* dataset (see Supporting Information S.4). Consequently, we applied robust maximum likelihood estimation for the fitting of this model and report robust values. There were no multivariate outliers in any of the datasets. See Tables S.5.1 and S.5.2 for fit indices, results from the chi-squared tests, and parameter estimates of all following models.

The chi-squared tests were nonsignificant and fit indices indicated a good (*vowel*) or acceptable (*consonant*) model fit for the proposed models. Both models fit the data significantly better than models not including change, *consonant*: $\Delta\chi^2 = 12.22$, $\Delta df = 4$, $p = .016$, *vowel*: $\Delta\chi^2 = 11.53$, $\Delta df = 4$, $p = .021$, indicating that for both *deviant* types, a significant change in the first-order latent variable MMR amplitude over time could be assumed.

In both models, the third assessment point's loading on the slope indicated a nonlinear growth trajectory of MMR amplitude change over time. Thus, as a final step, we included a second slope into the models, such that the first slope described the MMR amplitude change between 2 and 6 months, and the second slope described the MMR amplitude change between 6 and 10 months.

Both the baseline *consonant* model and the two-slope *consonant* model described an approximately quadratic change in MMR amplitude (see Figure 3a). The intercept was estimated to be positive (1.83), and both estimated slope values were negative (2- to 6-month slope: −0.19; 6- to 10-month slope: −0.93). Thus, 2-month-old infants generally started with a positive MMR in response to the *consonant* contrast that decreased towards a negativity from 2 to 6 months to then decrease more strongly between 6 and 10 months (see Figure 3a). Covariance of intercept with both slopes was negative (2- to 6-month slope: cov = −3.14; 6- to 10-month slope: −2.71), indicating that infants with a more positive *consonant*-MMR amplitude at 2 months showed a stronger decrease in MMR amplitude from 2 to 6 months and 6 to 10 months. The covariance between both slopes was positive (cov = 1.41), suggesting that a stronger decrease in *consonant*-MMR amplitude from 2 to 6 months was associated with a stronger decrease from 6 to 10 months, too.

For the *vowel* contrast, both the baseline and the two-slope-model described an inverted u-shaped trajectory

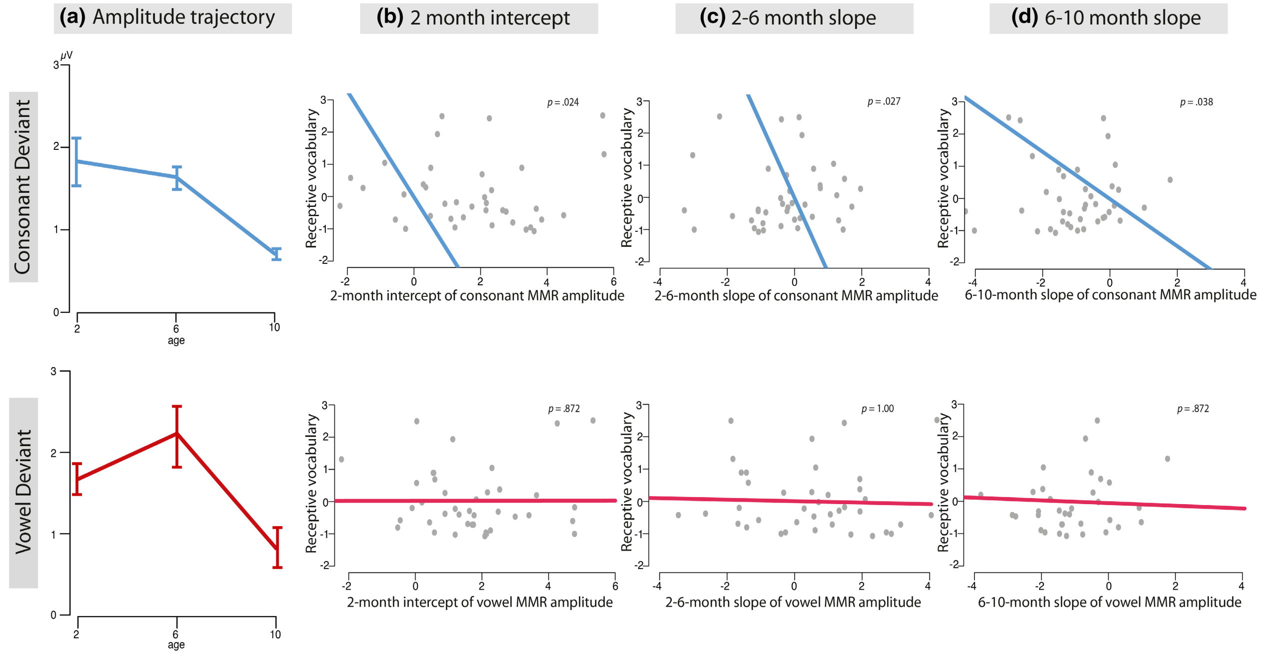

**FIGURE 3** Mismatch response (MMR) amplitude growths curves and regression of standardized receptive vocabulary scores at 12 months on estimated intercept and slope values for MMR amplitudes. Growth curves of MMR amplitudes and regression of standardized receptive vocabulary scores at 12 months (assessed via the German version of the MacArthur-Bates Communicative Development Inventories, Children's Depression Inventory [CDI]; Elternfragebögen für die Früherkennung von Risikokindern [ELFRA-1]; Grimm & Doil, 2000) on estimated intercept and slope values for MMR amplitudes. (a) Amplitude trajectories from 2 to 10 months, illustrated by the mean amplitudes of *consonant* (upper panel, blue) and *vowel* (lower panel, red) MMRs across assessment points as estimated by the growth curve models ($n = 58$). Bars represent standard errors. (b) Regression of receptive vocabulary scores at 12 months (assessed via the German version of the MacArthur-Bates Communicative Development Inventories, CDI; ELFRA-1; Grimm & Doil, 2000) on estimated *consonant* (upper panel, blue) and *vowel* 2-month intercept (lower panel, red). Dots represent the original or uncontrolled data, whereas the regression line represents the association between receptive vocabulary and intercept controlled for 2- to 6-month and 6- to 10-month MMR slopes ($n = 40$). (c) Regression of receptive vocabulary scores on estimated 2- to 6-month *consonant* (upper panel, blue) and *vowel*-MMR slope (lower panel, red). Dots represent the original or uncontrolled data, whereas the regression line represents the association between receptive vocabulary and 2- to 6-month slope controlled for 2-month MMR amplitude and 6- to 10-month MMR slope ($n = 40$). (d) Regression of receptive vocabulary scores on estimated 6- to 10-month *consonant* (upper panel, blue) and *vowel*-MMR slope (lower panel, red). Dots represent the original or uncontrolled data, whereas the regression line represents the association between receptive vocabulary and 2- to 6-month slope controlled for 2-month MMR amplitude and 2- to 6-month MMR slope ($n = 40$).

**TABLE 2** Linear multiple regression models analyzing the predictive value of the 2- to 6-month slope, the 6- to 10-month slope, and the intercept from the consonant model for productive and receptive vocabulary at 12 months, respectively. $p$-Values are corrected for multiple comparisons using the Holm-Bonferroni method

| Model | Predictors | $b$ | $\beta$ | $t(36)$ | $p_{corr}$ |
|---|---|---|---|---|---|
| Receptive vocabulary at 12 months | 2- to 6-month slope | −105.00 | −2.95 | −2.77 | .027 |
| | 6- to 10-month slope | −33.15 | −.91 | −2.45 | .038 |
| | Intercept | −74.32 | −3.76 | −2.93 | .024 |
| Productive vocabulary at 12 months | 2- to 6-month slope | −1.15 | −.22 | −.19 | 1.00 |
| | 6- to 10-month slope | −0.17 | −.03 | −.08 | 1.00 |
| | Intercept | −0.16 | −.06 | −.04 | 1.00 |

(see Figure 3a). Estimated values for the intercept (1.67) and the 2- to 6-month slope (0.56) were positive, whereas the 6- to 10-month slope was estimated to be negative (−1.41): Infants showed positive MMR amplitudes in reaction to the *vowel* contrasts at 2 months, which increased between 2 and 6 months and then decreased between 6 and 10 months towards a more negative amplitude than was observed at 2 months (see Figure 3a). The covariance between intercept and the 2- to 6-month slope was small and positive (cov = 0.48), while the intercept and the 6- to 10-month slope covaried negatively (cov = −2.35). This indicates that infants with a more positive 2-month *vowel*-MMR amplitude had a slightly stronger increase in *vowel*-MMR amplitude from 2 to 6 months and a stronger decrease in *vowel*-MMR amplitude from 6 to 10 months. Both slopes had a small, positive covariance (cov = 0.47), suggesting that a stronger increase in *vowel*-MMR amplitude from 2 to 6 months was associated with a smaller decrease in *vowel*-MMR amplitude from 6 to 10 months.

## Association of speech perception development with productive and receptive vocabulary

For productive vocabulary, we observed a *mean* score of 4.08 (SD = 6.47, maximum possible score: 164) and for receptive vocabulary, we observed a *mean* score of 52.15 (SD = 44.90, maximum possible score: 164).

Analyzing the association of the *consonant* MMR's maturational slopes and the intercept (i.e., 2-month MMR) with productive and receptive vocabulary in two separate multiple regression models, we found that receptive vocabulary was significantly negatively predicted by the 2- to 6-month consonant slope, the 6- to 10-month consonant slope, and the consonant intercept, $R^2 = .20$, $R^2_{\text{corr}} = .13$, $F(3, 36) = 2.92$, $p = .047$ (see Table 2), whereas productive vocabulary was not significantly predicted by any included variable, $R^2 = .04$, $R^2_{\text{corr}} = -.04$, $F(3, 36) = 0.47$, $p = .707$ (see Table 2; Figure 3b–d). Thus, a more negative (i.e., more mature) 2-month *consonant* MMR and a stronger change in *consonant*-MMR amplitude from 2 to 6 and 6 to 10 months towards less positive (i.e., more negative or mature) amplitudes predicted higher receptive vocabulary scores at 12 months.

For the vowel slopes and intercept, there was no significant association between the 2- to 6-month vowel slope, the 6- to 10-month vowel slope, or the vowel intercept with receptive vocabulary, $R^2 = .05$, $R^2_{\text{corr}} = -.03$, $F(3, 36) = 0.67$, $p = .576$, and neither with productive vocabulary, $R^2 = .11$, $R^2_{\text{corr}} = .04$, $F(3, 36) = 1.50$, $p = .232$ (see Table 3; Figure S.5).

For additional analyses with single time point *consonant* and *vowel*-MMR amplitudes at 2, 6, and 10 months predicting receptive and productive vocabulary scores, we found the 6-month *consonant* MMR to be associated with later receptive vocabulary scores (see Supporting Information S.7). The Supporting Information also contains additional analyses with *frequency* and *vowel-length* maturational slopes and intercepts (i.e., for the other two deviants from the multifeature paradigm) as predictors of receptive and productive vocabulary (S.8).

# DISCUSSION

The present study aimed to investigate how the developmental trajectory of consonant and vowel perception across the first year of life associates with infants' lexical skills at 12 months using electrophysiological measures. To determine the developmental trajectory of consonant and vowel perception, we longitudinally measured the infant MMR to *consonant* and *vowel* changes when infants were 2, 6, and 10 months of age and modeled the longitudinal MMR amplitude trajectory in second-order LGMs. The resulting maturational MMR slopes and intercepts were used to predict infants' productive and receptive vocabulary (parental questionnaire) at the age of 12 months. For both, consonant and vowel perception, we found positive MMR amplitudes across all assessment points, with an amplitude decrease across age. Only for consonant perception, this decrease in amplitude related to later receptive vocabulary.

Within the first year of life, the brain's signature of auditory discrimination is expected to develop from a p-MMR to an n-MMR (e.g., Friedrich et al., 2009; Trainor et al., 2003). Even though we observed p-MMRs across all assessment points for both consonant and vowel changes, we could show that the MMR amplitudes became less positive with age, indicating a shift towards a negativity (see also, e.g., Cheng et al., 2015; Trainor et al., 2003). As n-MMRs or MMNs are commonly observed in older children and adults (Näätänen et al., 2007; Schaadt & Männel, 2019), we interpret the decrease in positivity to reflect the development towards a more mature, adult-like brain response. In addition to the decrease in p-MMR amplitude, we observed a negativity preceding the p-MMR for the *vowel* contrast at 6 and 10 months. However, this negativity started 92 ms (at 6 months) and 78 ms (at 10 months) after deviation onset of the *vowel* contrast. As the n-MMR in response to *vowel* deviants usually starts 150 ms after deviation onset in infants at that age (e.g., Cheng et al., 2015) and as we were specifically

**TABLE 3** Linear multiple regression models analyzing the predictive value of the 2–6 month slope, the 6- to 10-month slope, and the intercept from the vowel model for productive and receptive vocabulary at 12 months, respectively. *p*-Values are corrected for multiple comparisons using the Holm-Bonferroni method

| Model | Predictors | *b* | *β* | *t*(36) | $p_{\text{corr}}$ |
|---|---|---|---|---|---|
| Receptive vocabulary at 12 months | 2- to 6-month slope | −1.10 | −.05 | −.22 | 1.00 |
| | 6- to 10-month slope | −24.06 | −.88 | −1.25 | .872 |
| | Intercept | −22.70 | −.83 | −1.09 | .872 |
| Productive vocabulary at 12 months | 2- to 6-month slope | 0.00 | .00 | .003 | 1.00 |
| | 6- to 10-month slope | 0.35 | .09 | .13 | 1.00 |
| | Intercept | 1.65 | .42 | .57 | 1.00 |

interested in the development of the p-MMR as an indicator of advancing language skills (e.g., Garcia-Sierra et al., 2016; Kuhl & Rivera-Gaxiola, 2008), we did not further consider these negativities. Notably, trajectories of the p-MMR amplitude development differed between *consonant* and *vowel* discrimination: The *consonant*-MMR amplitude decreased towards a negativity in a quadratic growth curve from 2 to 10 months, with a smaller decrease from 2 to 6 months and a pronounced decrease from 6 to 10 months. In contrast, the *vowel*-MMR amplitude changed in an inverted u-shape with an initial increase (i.e., more positive) from 2 to 6 months, followed by a decrease (i.e., less positive, or more negative) from 6 to 10 months. Independent of the growth curve's shape, both *consonant* and *vowel* MMRs became less positive and thus more mature across development (for a detailed discussion of growth curve shapes, see Werwach et al., 2022).

Importantly, we observed that only consonant perception across the first year of life was associated with receptive but not productive vocabulary at age 12 months. This means that (1) a more mature (i.e., less positive MMR or more negative MMR amplitude) consonant perception at 2 months (intercept), (2) a more mature (i.e., less positive MMR or more negative MMR amplitude) consonant perception at 6 months (single time point *consonant* MMR), and (3) a faster maturation of consonant perception from 2 to 6 and 6 to 10 months (i.e., stronger decrease in *consonant*-MMR amplitude; slope values) is associated with a larger receptive vocabulary at 12 months. For vowel perception, we did not find any significant association, neither with receptive nor with productive vocabulary. These results suggest that for German-learning infants, consonants play a key role for later vocabulary acquisition from early on, supporting the proposal that consonants mainly contribute to lexical acquisition (Hochmann et al., 2011). Strikingly, the maturational trajectory of the *consonant* MMR from 2 to 6 months was more strongly associated with later receptive vocabulary than the maturational trajectory between 6 and 10 months, and already the 2-month *consonant*-MMR amplitude (i.e., intercept), as well as the 6-month *consonant*-MMR amplitude (i.e., single time point regression analysis, see S.7) predicted receptive vocabulary at 12 months. Since behaviorally, a vowel bias is found in German-learning 9-month-olds (Schmandt et al., 2022), our results suggest that the longitudinal development of consonant perception has relevance for later vocabulary. This perceptual relevance seems to be present some time before the consonant bias is apparent in lexical processing. We suggest that early mature consonant perception supports infants in recognizing the advantage of consonants over vowels in lexical processing, an important prerequisite of the consonant bias, which bootstraps lexical acquisition, as suggested by the acoustic-phonetic hypothesis (Floccia et al., 2014; Nespor et al., 2003).

Our results did not reveal an association of either consonant or vowel perception with later productive vocabulary. Previous studies assessing infants' lexical processing (in contrast to the phonological processing investigated in this study) showed general phoneme perception (i.e., consonant and vowels) at 8 months to positively predict productive vocabulary growth from 16 to 24 months (Von Holzen et al., 2018) and sensitivity to consonants at 11 months to negatively predict productive vocabulary growth from 11 to 24 months (Von Holzen & Nazzi, 2020). The lacking association of phoneme perception with later productive vocabulary in our study might be explained by the small productive vocabulary and low variability in children around their first birthday. Parents of our study reported a *mean* of 4.08 (SD = 6.47) of produced words, ranging from 0 to 39 words. Consequently, the expected pattern of a positive influence of the maturation of consonant perception on productive vocabulary might be obliterated (for similar argumentation, see Von Holzen & Nazzi, 2020). As receptive vocabulary development precedes productive vocabulary development, infants show higher variability in this skill at the age of 12 months (i.e., in our study, $M = 52.15$, SD = 44.9, range = 3–164 words), which likely allowed us to uncover the positive association between consonant perception and vocabulary size in this study. Thus, future studies need to investigate a potential long-term advantage of consonant perception for productive vocabulary by following children's vocabulary growth beyond their first birthday.

Contrary to our differential results of consonant versus vowel perception for lexical acquisition, Von Holzen et al. (2018) found general phoneme sensitivity, that is, more mature ERP responses to both consonant and vowel changes in words, to relate to later vocabulary acquisition. In their study, however, the predictive value of vowel and consonant perception might be explained by the fact that phoneme sensitivity was tested exactly at the age (i.e., 8 months) when the shift from vowel- to consonant bias is expected to occur (Nishibayashi & Nazzi, 2016). Moreover, testing phoneme sensitivity was embedded in a lexical task (i.e., word segmentation), in contrast to a purely phonological task used in our study. In addition, methodological differences related to the experimental paradigm, analytic strategy and the time of productive vocabulary assessment might have contributed to the fact that we did not find any association of vowel perception with vocabulary. Even though there was no association of vowel perception and lexical acquisition in our study, we do not question the fact that both consonant and vowel perception are essential to successfully acquiring a native language. While a consonant bias refers to the preferential processing of consonants in lexical tasks, vowels are likewise essential for the identification of the correct word. Additionally, the consonant bias in lexical processing is contrasted with a vowel bias in the acquisition of grammatical rules (see

Hochmann et al., 2011), which, together with individual words, are the building blocks of language.

## Limitations

In the current study, we did not investigate lexical processing or infants' vowel- and consonant biases directly, but instead focused on phonological processing, which is closely interrelated with lexical acquisition (see Johnson, 2016; Werker & Yeung, 2005) and has been assigned a central role in both the acoustic-phonetic as well as the phono-lexical account of the development of lexical biases in children (see Bonatti et al., 2007; Floccia et al., 2014; Poltrock & Nazzi, 2015). Thus, we investigated the longitudinal development of infants' vowel- and consonant perception in relation to lexical acquisition as a potential precursor to later lexical biases.

As the development of the MMR to speech contrasts and the developmental trajectory of vowel- and consonant biases in lexical processing are modulated by infants' language background, conclusions drawn from our study are limited to infants from monolingual German families. For our results to be generalized, studies in other languages examining infants' maturation of consonant and vowel-perception skills in relation to later vocabulary are needed. Since we only tested one consonant and one vowel contrast, future studies should also include additional contrasts to assess the generalizability of our results.

Further, the MMR's amplitude and polarity are also associated with experimental design and stimulus features, such as acoustic salience of the tested stimuli and magnitude of deviance (Cheng & Lee, 2018; Cheng et al., 2013, 2015). In other words, potential differences in the acoustic salience of consonant and vowel deviants in our study, rather than phoneme categories per se, might lead to differential effects of difficult discrimination (i.e., less salient contrasts like consonants) and easier discrimination (i.e., more salient contrasts like vowels) on lexical acquisition. Within this explanation, more mature perception of the more difficult contrast (i.e., less salient consonant contrast) might have supported infants in recognizing the advantage of consonants over vowels in lexical processing, an important prerequisite of the consonant bias.

We acknowledge that while the MMN has shown good test–retest reliability for specific speech contrasts in adults (Tervaniemi et al., 1999; Wang et al., 2021), there is currently no data available on the test–retest reliability of the infant MMR that could prove the MMRs' suitability for longitudinal designs.

Lastly, as pointed out above, we observed very little variance in infants' productive vocabulary scores at 12 months. We nevertheless included productive vocabulary as an outcome measure in our exploratory study, as previous studies on the association between vowel- and consonant biases and vocabulary focused on productive vocabulary (Von Holzen & Nazzi, 2020; Von Holzen et al., 2018). However, future studies should assess productive vocabulary at age points that are more informative about infants' language development.

# CONCLUSION

In the present study using electrophysiological measures we demonstrated a prominent role of consonant perception for vocabulary development from early on in life, even months before the behavioral onset of consonant preferences in word recognition (i.e., 8 months; Nishibayashi & Nazzi, 2016; Poltrock & Nazzi, 2015). We found that consonant perception at 2 months as well as the longitudinal development of this perceptive ability from 2 to 6 months and 6 to 10 months is predictive of German children's later receptive vocabulary. Thus, the predictive value of speech perception trajectories should be considered in future studies on children's language development.

## ACKNOWLEDGMENTS

This research was funded by the German Research Foundation (project MA 6897/2-1, awarded to CM). We are grateful to the participating families for supporting our research and thank Kristiane Klein and Lisa-Marie Burmeister for their help in data collection. Open Access funding enabled and organized by Projekt DEAL.

## DATA AVAILABILITY STATEMENT

The data and analytic code necessary to reproduce the analyses, as well as the materials necessary to attempt to replicate the findings presented are not publicly accessible. The analyses presented here were not preregistered.

## ORCID

*Gesa Schaadt* https://orcid.org/0000-0002-3192-3698

## REFERENCES

Alho, K., Woods, D. L., & Algazi, A. (1994). Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials. *Psychophysiology*, *31*(5), 469–479. https://doi.org/10.1111/j.1469-8986.1994.tb01050.x

Benavides-Varela, S., Hochmann, J. R., Macagno, F., Nespor, M., & Mehler, J. (2012). Newborn's brain activity signals the origin of word memories. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(44), 17908–17913. https://doi.org/10.1073/pnas.1205413109

Boersma, P. (2001). Praat, a system for doing phonetics by computer. *Glot International*, *5*(9), 341–345.

Bonatti, L. L., Pena, M., Nespor, M., & Mehler, J. (2007). On consonants, vowels, chickens, and eggs. *Psychological Science*, *18*(10), 924–925.

Bouchon, C., Floccia, C., Fux, T., Adda-Decker, M., & Nazzi, T. (2015). Call me Alix, not Elix: Vowels are more important than consonants in own-name recognition at 5 months. *Developmental Science*, *18*(4), 587–598. https://doi.org/10.1111/desc.12242

Bouchon, C., Hochmann, J. R., & Toro, J. M. (2022). Spanish-learning infants switch from a vowel to a consonant bias during the first year of life. *Journal of Experimental Child Psychology*, *221*, 105444. https://doi.org/10.1016/j.jecp.2022.105444

Chen, H., Lee, D. T., Luo, Z., Lai, R. Y., Cheung, H., & Nazzi, T. (2021). Variation in phonological bias: Bias for vowels, rather than consonants or tones in lexical processing by Cantonese-learning toddlers. *Cognition*, *213*, 104486. https://doi.org/10.1016/j.cognition.2020.104486

Cheng, Y. Y., & Lee, C. Y. (2018). The development of mismatch responses to mandarin lexical tone in 12- to 24-month-old infants. *Frontiers in Psychology*, *9*, 448. https://doi.org/10.3389/fpsyg.2018.00448

Cheng, Y.-Y., Wu, H.-C., Tzeng, Y.-L., Yang, M.-T., Zhao, L.-L., & Lee, C.-Y. (2013). The development of mismatch responses to mandarin lexical tones in early infancy. *Developmental Neuropsychology*, *38*(5), 281–300. https://doi.org/10.1080/87565641.2013.799672

Cheng, Y.-Y., Wu, H.-C., Tzeng, Y.-L., Yang, M.-T., Zhao, L.-L., & Lee, C.-Y. (2015). Feature-specific transition from positive mismatch response to mismatch negativity in early infancy: Mismatch responses to vowels and initial consonants. *International Journal of Psychophysiology*, *96*(2), 84–94. https://doi.org/10.1016/j.ijpsycho.2015.03.007

Cheour, M., Leppänen, P., & Kraus, N. (2000). Mismatch negativity (MMN) as a tool for investigating auditory discrimination and sensory memory in infants and children. *Clinical Neurophysiology*, *111*(1), 4–16. https://doi.org/10.1016/S1388-2457(99)00191-1

Cheour-Luthanen, M., Alho, K., Kujala, T., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (1995). Mismatch negativity indicates vowel discrimination in newborns. *Hearing Research*, *82*(1), 53–58.

Curran, P. J., Obeidat, K., & Losardo, D. (2010). Twelve frequently asked questions about growth curve modeling. *Journal of Cognition and Development*, *11*(2), 121–136. https://doi.org/10.1080/15248371003699969

Dehaene-Lambertz, G. (2000). Cerebral specialization for speech and non-speech stimuli in infants. *Journal of Cognitive Neuroscience*, *12*(3), 449–460. https://doi.org/10.1162/089892900562264

Dehaene-Lambertz, G., & Dehaene, S. (1994). Speed and cerebral correlates of syllable discrimination in infants. *Nature*, *370*(6487), 292–295. https://doi.org/10.1038/370292a0

Dehaene-Lambertz, G., & Pena, M. (2001). Electrophysiological evidence for automatic phonetic processing in neonates. *Neuroreport*, *12*(14), 3155–3158. https://doi.org/10.1097/00001756-200110080-00034

Dehaene-Lambertz, G., & Spelke, E. S. (2015). The infancy of the human brain. *Neuron*, *88*(1), 93–109. https://doi.org/10.1016/j.neuron.2015.09.026

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Draganova, R., Eswaran, H., Murphy, P., Huotilainen, M., Lowery, C., & Preissl, H. (2005). Sound frequency change detection in fetuses and newborns, a magnetoencephalographic study. *NeuroImage*, *28*(2), 354–361. https://doi.org/10.1016/j.neuroimage.2005.06.011

Duncan, T. E., & Duncan, S. C. (2009). The ABC's of LGM: An introductory guide to latent variable growth curve modeling. *Social and Personality Psychology Compass*, *3*(6), 979–991. https://doi.org/10.1111/j.1751-9004.2009.00224.x

Fenson, L. (2002). *MacArthur communicative development inventories: User's guide and technical manual*. Paul H. Brookes.

Floccia, C., Nazzi, T., Delle Luche, C., Poltrock, S., & Goslin, J. (2014). English-learning one- to two-year-olds do not show a consonant bias in word learning. *Journal of Child Language*, *41*(5), 1085–1114. https://doi.org/10.1017/S0305000913000287

Friederici, A. D. (2006). The neural basis of language development and its impairment. *Neuron*, *52*(6), 941–952. https://doi.org/10.1016/j.neuron.2006.12.002

Friederici, A. D., Friedrich, M., & Christophe, A. (2007). Brain responses in 4-month-old infants are already language specific. *Current Biology*, *17*(14), 1208–1211. https://doi.org/10.1016/j.cub.2007.06.011

Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *Neuroreport*, *13*(10), 1251–1254. https://doi.org/10.1097/00001756-200207190-00006

Friedrich, M., Herold, B., & Friederici, A. D. (2009). ERP correlates of processing native and non-native language word stress in infants with different language outcomes. *Cortex*, *45*(5), 662–676. https://doi.org/10.1016/j.cortex.2008.06.014

Friedrich, M., Weber, C., & Friederici, A. D. (2004). Electrophysiological evidence for delayed mismatch response in infants at-risk for specific language impairment. *Psychophysiology*, *41*(5), 772–782. https://doi.org/10.1111/j.1469-8986.2004.00202.x

Garcia-Sierra, A., Ramírez-Esparza, N., & Kuhl, P. K. (2016). Relationships between quantity of language input and brain responses in bilingual and monolingual infants. *International Journal of Psychophysiology*, *110*, 1–17. https://doi.org/10.1016/j.ijpsycho.2016.10.004

Gómez, D. M., Mok, P., Ordin, M., Mehler, J., & Nespor, M. (2018). Statistical speech segmentation in tone languages—The role of lexical tones. *Language and Speech*, *61*(1), 84–96.

Gonzalez, R., & Griffin, D. (2001). Testing parameters in structural equation modeling: Every "one" matters. *Psychological Methods*, *6*(3), 258–269. https://doi.org/10.1037/1082-989X.6.3.258

Grimm, H., & Doil, H. (2000). *Elternfragebögen für die Früherkennung von Risikokindern: ELFRA*. Hogrefe, Verlag für Psychologie.

He, C., Hotson, L., & Trainor, L. J. (2007). Mismatch responses to pitch changes in early infancy. *Journal of Cognitive Neuroscience*, *19*(5), 878–892. https://doi.org/10.1162/jocn.2007.19.5.878

He, C., Hotson, L., & Trainor, L. J. (2009). Maturation of cortical mismatch responses to occasional pitch change in early infancy: Effects of presentation rate and magnitude of change. *Neuropsychologia*, *47*(1), 218–229. https://doi.org/10.1016/j.neuropsychologia.2008.07.019

Henze, N., & Zirkler, B. (1990). A class of invariant consistent tests for multivariate normality. *Communications in statistics—Theory and Methods*, *19*(10), 3595–3617. https://doi.org/10.1080/03610929008830400

Hochmann, J. R., Benavides-Varela, S., Fló, A., Nespor, M., & Mehler, J. (2018). Bias for vocalic over consonantal information in 6-month-olds. *Infancy*, *23*(1), 136–151. https://doi.org/10.1111/infa.12203

Hochmann, J. R., Benavides-Varela, S., Nespor, M., & Mehler, J. (2011). Consonants and vowels: Different roles in early language acquisition. *Developmental Science*, *14*(6), 1445–1458. https://doi.org/10.1111/j.1467-7687.2011.01089.x

Hojen, A., & Nazzi, T. (2016). Vowel bias in Danish word-learning: Processing biases are language-specific. *Developmental Science*, *19*(1), 41–49. https://doi.org/10.1111/desc.12286

Hooper, D., Coughlan, J., & Mullen, M. (2008). Structural equation modelling: Guidelines for determining model fit. *Electronic Journal of Business Research Methods*, *6*(1), 53–60.

Jeon, M., & Kim, S.-Y. (2020). Performance of second-order latent growth model under partial longitudinal measurement invariance: A comparison of two scaling approaches. *Structural Equation Modeling*, *28*(2), 261–277. https://doi.org/10.1080/10705511.2020.1783270

Johnson, E. K. (2016). Constructing a proto-lexicon: An integrative view of infant language development. *Annual Review of Linguistics*, *2*(1), 391–412. https://doi.org/10.1146/annurev-linguistics-011415-040616

Keidel, J. L., Jenison, R. L., Kluender, K. R., & Seidenberg, M. S. (2007). Does grammar constrain statistical learning. *Psychological Science*, *18*(10), 922–923.

Koerner, T. K., Zhang, Y., Nelson, P. B., Wang, B., & Zou, H. (2016). Neural indices of phonemic discrimination and sentence-level speech intelligibility in quiet and noise: A mismatch negativity study. *Hearing Research*, *339*, 40–49. https://doi.org/10.1016/j.heares.2016.06.001

Korkmaz, S., Goksuluk, D., & Zararsiz, G. (2014). MVN: An R package for assessing multivariate normality. *The R Journal*, *6*(2), 151–162. https://doi.org/10.32614/RJ-2014-031

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews. Neuroscience*, *5*(11), 831–843. https://doi.org/10.1038/nrn1533

Kuhl, P. K., Conboy, B. T., Coffey-Corina, S., Padden, D., Rivera-Gaxiola, M., & Nelson, T. (2008). Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e). *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1493), 979–1000. https://doi.org/10.1098/rstb.2007.2154

Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: Implications for the "critical period". *Language Learning and Development*, *1*(3–4), 237–264. https://doi.org/10.1080/15475441.2005.9671948

Kuhl, P. K., & Rivera-Gaxiola, M. (2008). Neural substrates of language acquisition. *Annual Review of Neuroscience*, *31*, 511–534. https://doi.org/10.1146/annurev.neuro.30.051606.094321

Kushnerenko, E. V., Balan, P., & Fellman, V. (2002). Maturation of the auditory change detection response in infants: A longitudinal ERP study. *Neuroreport*, *13*(15), 1843–1848.

Labonte-Lemoyne, E., Curnier, D., & Ellemberg, D. (2017). Exercise during pregnancy enhances cerebral maturation in the newborn: A randomized controlled trial. *Journal of Clinical and Experimental Neuropsychology*, *39*(4), 347–354. https://doi.org/10.1080/13803395.2016.1227427

Leppänen, P. H. T., Eklund, K. M., & Lyytinen, H. (1997). Event-related brain potentials to change in rapidly presented acoustic stimuli in newborns. *Developmental Neuropsychology*, *13*(2), 175–204. https://doi.org/10.1080/87565649709540677

Little, T. D., Slegers, D. W., & Card, N. A. (2006). A non-arbitrary method of identifying and scaling latent variables in SEM and MACS models. *Structural Equation Modeling*, *13*(1), 59–72. https://doi.org/10.1207/s15328007sem1301_3

Lovio, R., Pakarinen, S., Huotilainen, M., Alku, P., Silvennoinen, S., Näätänen, R., & Kujala, T. (2009). Auditory discrimination profiles of speech sound changes in 6-year-old children as determined with the multi-feature MMN paradigm. *Clinical Neurophysiology*, *120*(5), 916–921. https://doi.org/10.1016/j.clinph.2009.03.010

Mahmoudzadeh, M., Dehaene-Lambertz, G., Fournier, M., Kongolo, G., Goudjil, S., Dubois, J., Grebe, R., & Wallois, F. (2013). Syllabic discrimination in premature human infants prior to complete formation of cortical layers. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(12), 4846–4851. https://doi.org/10.1073/pnas.1212220110

Makeig, S., Bell, A. J., Jung, T.-P., & Sejnowski, T. J. (1996). Independenct component analysis of electroencephalographic data. *Advances in Neural Information Processing Systems*, *8*, 145–151.

Männel, C., Schaadt, G., Illner, F. K., van der Meer, E., & Friederici, A. D. (2017). Phonological abilities in literacy-impaired children: Brain potentials reveal deficient phoneme discrimination, but intact prosodic processing. *Developmental Cognitive Neuroscience*, *23*, 14–25. https://doi.org/10.1016/j.dcn.2016.11.007

Mardia, K. V. (1980). Tests of univariate and multivariate normality. *Handbook of Statistics*, *1*, 279–320.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Morr, M. L., Shafer, V. L., Kreuzer, J. A., & Kurtzberg, D. (2002). Maturation of mismatch negativity in typically developing infants and preschool children. *Ear and Hearing*, *23*(2), 118–136. https://doi.org/10.1097/00003446-200204000-00005

Mosca, R., Kritzinger, A., & van der Linde, J. (2015). Language and communication development in preschool children with visual impairment: A systematic review. *The South African Journal of Communication Disorders*, *62*(1), e1–e10. https://doi.org/10.4102/sajcd.v62i1.119

Mueller, J. L., Friederici, A. D., & Männel, C. (2012). Auditory perception at the root of language learning. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(39), 15953–15958. https://doi.org/10.1073/pnas.1204319109

Näätänen, R., & Alho, K. (1997). Mismatch negativity—The measure for central sound representation accuracy. *Audiology & Neuro-Otology*, *2*(5), 341–353. https://doi.org/10.1159/000259255

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: A review. *Clinical Neurophysiology*, *118*(12), 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026

Näätänen, R., Paavilainen, P., Titinen, H., Jiang, D., & Alho, K. (1993). Attention and mismatch negativity. *Psychophysiology*, *30*(5), 436–450. https://doi.org/10.1111/j.1469-8986.1993.tb02067.x

Näätänen, R., Pakarinen, S., Rinne, T., & Takegata, R. (2004). The mismatch negativity (MMN): Towards the optimal paradigm. *Clinical Neurophysiology*, *115*(1), 140–144. https://doi.org/10.1016/j.clinph.2003.04.001

Nazzi, T., & Cutler, A. (2019). How consonants and vowels shape spoken-language recognition. *Annual Review of Linguistics*, *5*, 25–47. https://doi.org/10.1146/annurev-linguistics-

Nazzi, T., Floccia, C., Moquet, B., & Butler, J. (2009). Bias for consonantal over vocalic information in French-and English-learning 30-month-olds: Crosslinguistic evidence in early word learning. *Journal of Experimental Child Psychology*, *102*, 522–537.

Nespor, M., Pena, M., & Mehler, J. (2003). On the different roles of vowels and consonants in speech processing and language acquisition. *Lingue e Linguaggio*, *2*(2), 203–230.

Neurobehavioral Systems Inc. (2014). *Presentation® software* (Version version 17.2). Neurobehavioral Systems Inc.

Nishibayashi, L. L., & Nazzi, T. (2016). Vowels, then consonants: Early bias switch in recognizing segmented word forms. *Cognition*, *155*, 188–203.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, *2011*, 156869.

Pakarinen, S., Lovio, R., Huotilainen, M., Alku, P., Näätänen, R., & Kujala, T. (2009). Fast multi-feature paradigm for recording several mismatch negativities (MMNs) to phonetic and acoustic changes in speech sounds. *Biological Psychology*, *82*(3), 219–226. https://doi.org/10.1016/j.biopsycho.2009.07.008

Partanen, E., Pakarinen, S., Kujala, T., & Huotilainen, M. (2013). Infants' brain responses for speech sound changes in fast multi-feature MMN paradigm. *Clinical Neurophysiology*, *124*(8), 1578–1585. https://doi.org/10.1016/j.clinph.2013.02.014

Perani, D., Saccuman, M. C., Scifo, P., Anwander, A., Spada, D., Baldoli, C., Poloniato, A., Lohmann, G., & Friederici, A. D. (2011). Neural language networks at birth. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(38), 16056–16061. https://doi.org/10.1073/pnas.1102991108

Polka, L., & Werker, J. (1994). Developmental changes in perception of nonnative vowel contrasts. *Developmental Psychology: Human Perceptual Performance*, *20*(2), 421–435. https://doi.org/10.1037/0096-1523.20.2.421

Poltrock, S., Chen, H., Kwok, C., Cheung, H., & Nazzi, T. (2018). Adult learning of novel words in a non-native language: Consonants, vowels, and tones. *Frontiers in Psychology*, *9*, 1211. https://doi.org/10.3389/fpsyg.2018.01211

Poltrock, S., & Nazzi, T. (2015). Consonant/vowel asymmetry in early word form recognition. *Journal of Experimental Child Psychology*, *131*, 135–148.

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rivera-Gaxiola, M., Klarman, L., Garcia-Sierra, A., & Kuhl, P. K. (2005). Neural patterns to speech and vocabulary growth in American infants. *Neuroreport*, *16*(5), 495–498. https://doi.org/10.1097/00001756-200504040-00015

Rosseel, Y. (2012). Lavaan: An R package for structural equation modeling. *Journal of Statistical Software*, *48*(2), 1–36.

Satorra, A., & Bentler, P. M. (2001). A scaled difference chi-square test statistic for moment structure analysis. *Psychometrika*, *66*(4), 507–514. https://doi.org/10.1007/BF02296192

Schaadt, G., & Männel, C. (2019). Phonemes, words, and phrases: Tracking phonological processing in pre-schoolers developing dyslexia. *Clinical Neurophysiology*, *130*(8), 1329–1341. https://doi.org/10.1016/j.clinph.2019.05.018

Schaadt, G., Männel, C., van der Meer, E., Pannekamp, A., Oberecker, R., & Friederici, A. D. (2015). Present and past: Can writing abilities in school children be associated with their auditory discrimination capacities in infancy? *Research in Developmental Disabilities*, *47*, 318–333. https://doi.org/10.1016/j.ridd.2015.10.002

Schmandt, S., van Ommen, S., Menze, C., Höhle, B., & Nazzi, T. (2022). *Vowel bias in German-learning 9-month-olds: Perceiving consonant and vowel skeletons*. ICIS.

Shafer, V. L., Yu, Y. H., & Datta, H. (2010). Maturation of speech discrimination in 4- to 7-yr-old children as indexed by event-related potential mismatch responses. *Ear and Hearing*, *31*(6), 735–745. https://doi.org/10.1097/AUD.0b013e3181e5d1a7

Singh, L., Goh, H. H., & Wewalaarachchi, T. D. (2015). Spoken word recognition in early childhood: Comparative effects of vowel, consonant and lexical tone variation. *Cognition*, *142*, 1–11. https://doi.org/10.1016/j.cognition.2015.05.010

Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*, *38*(4), 387–401.

Tervaniemi, M., Lehtokoski, A., Sinkkonen, J., Virtanen, J., Ilmoniemi, R. J., & Näätänen, R. (1999). Test-retest reliability of mismatch negativity for duration, frequency and intensity changes. *Clinical Neurophysiology*, *110*, 1388–1393.

The Math Works, I. (2020). MATLAB. In (Version version 9.9 (R2020a)).

Trainor, L. J., McFadden, M., Hodgson, L., Darragh, L., Barlow, J., Matsos, L., & Sonnadara, R. (2003). Changes in auditory cortex and the development of mismatch negativity between 2 and 6 months of age. *International Journal of Psychophysiology*, *51*(1), 5–15. https://doi.org/10.1016/S0167-8760(03)00148-X

Von Holzen, K., & Nazzi, T. (2020). Emergence of a consonant bias during the first year of life: New evidence from own-name recognition. *Infancy*, *25*(3), 319–346. https://doi.org/10.1111/infa.12331

Von Holzen, K., Nishibayashi, L. L., & Nazzi, T. (2018). Consonant and vowel processing in word form segmentation: An infant ERP study. *Brain Sciences*, *8*(2), 24. https://doi.org/10.3390/brainsci8020024

Wang, J., Chen, T., Jiao, X., Liu, K., Tong, S., & Sun, J. (2021). Test-retest reliability of duration-related and frequency-related mismatch negativity. *Neurophysiologie Clinique*, *51*(6), 541–548. https://doi.org/10.1016/j.neucli.2021.10.004

Werker, J. F., & Yeung, H. H. (2005). Infant speech perception bootstraps word learning. *Trends in Cognitive Sciences*, *9*(11), 519–527. https://doi.org/10.1016/j.tics.2005.09.003

Werner, C., Schermelleh-Engel, K., Gerhard, C., & Gäde, J. C. (2016). Strukturgleichungsmodelle. In *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften* (pp. 945–973). Springer. https://doi.org/10.1007/978-3-642-41089-5_17

Werwach, A., Männel, C., Obrig, H., Friederici, A. D., & Schaadt, G. (2022). Longitudinal trajectories of electrophysiological mismatch responses in infant speech discrimination differ across speech features. *Developmental Cognitive Neuroscience*, *56*, 101127. https://doi.org/10.1016/j.dcn.2022.101127

Wewalaarachchi, T. D., & Singh, L. (2020). Vowel, consonant, and tone variation exert asymmetrical effects on spoken word recognition: Evidence from 6-year-old monolingual and bilingual learners of mandarin. *Journal of Experimental Child Psychology*, *189*, 104698. https://doi.org/10.1016/j.jecp.2019.104698

Wiener, S., & Turnbull, R. (2016). Constraints of tones, vowels and consonants on lexical selection in mandarin Chinese. *Language and Speech*, *59*(Pt. 1), 59–82. https://doi.org/10.1177/0023830915578000

World Medical Association. (2013). World medical association declaration of Helsinki: Ethical principles for medical research involving human subjects. *Journal of the American Medical Association*, *310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Schaadt, G., Werwach, A., Obrig, H., Friederici, A. D., & Männel, C. (2023). Maturation of consonant perception, but not vowel perception, predicts lexical skills at 12 months. *Child Development*, *94*, e166–e180. https://doi.org/10.1111/cdev.13892