Bilingual Exposure and Sex Shape Developmental Trajectories of Brain Responses to Speech-Sound Features in Infants

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Highlights

- Bilingualism and sex impact early developmental trajectories in neural speech encoding
- Results suggest a female advantage in early neural encoding of speech-sound features
- Bilingual exposure positively modulates infant neural speech encoding

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Abstract

As the auditory brain becomes functional during the third trimester of pregnancy, both biological and environmental processes begin shaping its maturation, influencing how speech sounds are perceived. Biological factors, such as sex, introduce early genetic differences, while environmental experiences, like bilingualism, modulate the auditory input that infants receive. Although existing research highlights the impact of sex and bilingualism on the development of speech perception, the neural mechanisms remain unclear. In this study, we recorded frequency-following responses (FFRs) longitudinally, at birth, six months, and twelve months of age in 73 infants exposed to varying degrees of bilingual input. We modeled the developmental trajectories for neural encoding of voice pitch and speech formant structure, finding significant maturation during the first six months, followed by stabilization through the first year. Distinct developmental patterns emerged as a function of sex and bilingualism, revealing their influence on neural attunement to key speech-sound features. Bilingual exposure notably predicted lower neural pitch encoding values at six months, but higher values by twelve months. A positive effect of bilingualism on speech formant encoding was observed throughout the first year. These findings reveal how biological and environmental factors contribute to individual variability in early auditory development and speech acquisition.

Keywords: Speech encoding; infants; bilingualism; sex; Frequency-Following Response; auditory evoked potential

1. Introduction

Speech acquisition initiates at a very early developmental stage, as the auditory brain is already functional and able to process sounds since the beginning of the third trimester of pregnancy (Hepper & Shahidullah, 1994; Moore & Linthicum, 2007; Querleu et al., 1988; Ruben, 1995). It is around the 27th week of gestation that hearing becomes fully functional and the first fetal responses to sounds can be registered (Draganova et al., 2018; Schneider et al., 2001). At this fetal stage, the cochlea and the temporal lobe are formed and myelination appears through the brainstem and up to the auditory thalamus (Lavigne-Rebillard & Bagger-Sjöbäck, 1992; Moore et al., 1995; Moore & Linthicum, 2007). Although the exact acoustic features reaching the fetus remain unclear, intrauterine recordings suggest that the acoustic signal is altered by the maternal womb, which attenuates around 30dB frequencies above 500 Hz (Abrams et al., 2000; Gerhardt & Abrams, 1996, 2000). This filtering primarily preserves the prosodic features of speech, conveying the variations in pitch, loudness and rhythm, while suppressing the phonemic contrast information (Moon, 2017; Querleu et al., 1988).

It is during this early period that fetuses are first exposed to an acoustic environment, which significantly influences the development of their acoustic capacities (Arenillas Alcón et al., 2023; Gorina-Careta et al., 2024; Moon et al., 2013; Partanen et al., 2013b). For instance, daily music exposure during pregnancy has been shown to positively impact the neural encoding of speech sounds at birth (Arenillas Alcón et al., 2023). Similarly, prenatal exposure to a bilingual environment affects the neonatal acoustic sensitivity to speech frequencies (Gorina-Careta et al., 2024). Neonates also demonstrate distinct preferences that indicate prenatal acoustic learning and tuning to the prosody of their native language (DeCasper & Fifer, 1980; Fernald & Simon, 1984; Granier-Deferre et al., 2011; Moon et al., 1993, 2013). Indeed, prenatal exposure to

speech evoke enduring changes in neural dynamics that further support learning and memory (Mariani et al., 2023).

Shortly after birth, infants exhibit sensitivity to a wide range of linguistically significant distinctions (Gervain & Mehler, 2010; Martinez-Alvarez et al., 2023). Newborns are able to encode the pitch of speech sounds in an adult-like manner (Arenillas-Alcón et al., 2021) and discriminate between languages they have not been exposed to, provided those languages differ rhythmically (Byers-Heinlein et al., 2010; Mehler et al., 1988; Nazzi et al., 1998). However, language acquisition relies on the capacity to classify similar yet non-identical sounds into either different or equivalent phonetic categories according to the specific language, which is dependent on further postnatal linguistic exposure (Kuhl et al., 1992, 2003; Rivera□Gaxiola et al., 2005). By the age of six months, infants typically begin to perceive the variability inherent in each phonetic unit, which enables them to identify vowels typical of their mother tongue and alters their phonetic perception toward a native-like model (Kuhl et al., 1992; Maye et al., 2002). These developmental changes are reflected in a pronounced enhancement in neural encoding of speech sound features (Ribas-Prats et al., 2023b; Puertollano et al., 2024) and coincide with their first articulation of consonant-vowel sounds, marking the babbling stage (Oller, 1992).

Exposure to distinct linguistic environments further shape developmental trajectories for infant speech processing. Monolingual infants demonstrate precise discrimination among a wide range of native and non-native phonemic contrasts by seven months of age (Best & McRoberts, 2003; Cheour et al., 1998; Rivera□Gaxiola et al., 2005). Conversely, bilingual infants at the same age do not exhibit equivalent levels of native phoneme discrimination, with within-group variability depending on the amount of exposure to each language (Best et al., 2016; Garcia-Sierra et al., 2011). As infants

approach their first year of life, their speech perception undergoes an experience-driven perceptual narrowing, leading to a refined attunement to their native phoneme repertoire (Cheour et al., 1998; Kuhl et al., 2006; Werker et al., 1981) and typically aligning with their first word productions (Fenson et al., 1994). As their expertise in native phoneme contrasts develops, the ability to discriminate non-native phonemes diminishes, becoming minimal by the end of the first year (Rivera□Gaxiola et al., 2005; Tsao et al., 2006; Werker & Tees, 1984). Notably, the timing of these developmental milestones is influenced by the balance of language input, regardless of whether infants are raised in monolingual or bilingual settings (García-Sierra et al., 2011, 2016).

Alongside linguistic environments, sex is a significant biological factor influencing speech processing. Beginning in the second trimester of pregnancy, the extensive placental transmission of sex-steroid hormones shapes early speech development (Lust et al., 2010; Lutchmaya et al., 2001; Schaadt et al., 2015; Wermke et al., 2014). As early as one month after birth, female infants tend to outperform males in phonological discrimination (Friederici et al., 2008), a difference mediated by sex hormone levels that are also linked to articulatory skills at five months (i.e., babbling; Quast et al., 2016), and to later language abilities in childhood (Hollier et al., 2013; Schaadt et al., 2015). Additionally, vocabulary growth rates have been observed to be faster in female infants (Dailey & Bergelson, 2023), while male infants face a higher risk of experiencing language delays within the first three years of life (Whitehouse et al., 2012). Despite these findings, there is still limited research exploring how sex modulates the developmental trajectories of neural speech encoding during the first year of life.

Advancements in utilizing infant brain potentials have significantly pushed the study of neural mechanisms involved in speech perception and acquisition (Hervé et al., 2022). The frequency-following response (FFR) stands out as an auditory evoked potential that

139 captures neural synchronization along the auditory pathway in response to complex
140 sounds such as speech and music (Coffey et al., 2019; Gorina-Careta et al., 2021). FFR
141 recordings have proven to be a powerful tool for investigating the neural encoding of
142 speech sound features, such as pitch and fine spectrotemporal details that underlie
143 phoneme perception (Gorina-Careta et al., 2022; Krizman & Kraus, 2019). In infancy,
144 the FFR has been employed to characterize typical and atypical development of neural
145 speech encoding (Banai et al., 2005, 2009; Cunningham et al., 2001; Puertollano et al.,
146 2024; Ribas-Prats et al., 2019, 2022, 2023b, 2023a). It has also been used to study
147 biological and environmental influences on auditory processing, including sex-related
148 differences throughout development (Krizman et al., 2019, 2020), as well as the impact
149 of prenatal bilingual experiences in neonates (Gorina-Careta et al., 2024), and postnatal
150 experiences in children (Krizman et al., 2015) and adults (Skoe et al., 2017). However,
151 these crucial factors remain unexplored across the first year of life.

152 The present study aimed to uncover how age, perinatal bilingual experience, and sex
153 collectively shape neural speech-encoding mechanisms during the first year of life. To
154 this end, we recorded FFRs from infants with varying degrees of bilingual exposure and
155 examined their developmental trajectories regarding the neural encoding of voice pitch
156 and formant structure content. Building on previous research depicting neural encoding
157 achievements during the first six months of life, which stabilize by the first year
158 (Puertollano et al., 2024), we anticipated observing similar age-related effects.
159 Additionally, we sought to relate our findings to existing literature that highlights
160 distinct developmental trajectories in phoneme discrimination associated with
161 monolingual and bilingual experiences during infancy. We also expected to find sex-
162 related differences in infant neural encoding of speech sounds, consistent with previous
163 studies on speech processing variations.

2. Methods

2.1 Participants

73 healthy-term neonates (38 females; mean gestational age at birth = 39.73 ± 0.97 weeks; mean birth weight = 3288.8 ± 302.6 grams; mean age at evaluation = 1.62 ± 0.94 days after birth) were recruited at the Sant Joan de Déu Barcelona Children's Hospital (Catalonia, Spain) and followed-up at six (aged 5.36 to 7.40 months after birth; mean = 6.23 ± 0.37 months) and twelve months of age (aged 11.81 to 13.22 months after birth; mean = 12.39 ± 0.36 months).

All infants participating in this study were born at term after low-risk gestations, with an adequate birth weight for their gestational age (Figueras & Gratacós, 2014). Any diagnosed pathology or an Apgar score below 7 at 1 and 5 minutes after birth were considered as exclusion criteria. None of the infants presented any risk factors for hearing impairment, as per the Joint Committee on Infant Hearing guidelines (2019). As part of the standard medical routine to ensure auditory pathway integrity at birth, all neonates had passed the universal hearing screening test based on an automated auditory brainstem response system (ALGO 3i, Natus Medical Incorporated, San Carlos, CA).

Approval from the Bioethics Committee of SJD Barcelona Children's Hospital (Internal review board ID: PIC-185-19) was obtained for this study. Prior to the infant data collection, all parents or legal guardians signed an informed consent in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All data from this study is available upon inquiry to the corresponding author.

2.2 Language Exposure Measurement

Infants' prenatal linguistic exposure was evaluated through a retrospective questionnaire delivered to their mothers, as reported previously by our group (Gorina-Careta et al.,

2024). Prenatal acoustic environment was considered as monolingual (i.e., no months of exposure) when mothers reported speaking only one language during their last trimester of pregnancy, or as bilingual (i.e., three months of exposure) when they reported using two different languages during that period. Postnatal linguistic exposure was evaluated for their first year of life through the Language Exposure Assessment Tool (LEAT; DeAnda et al., 2016), which provided the total number of months of bilingual exposure. Prenatal and postnatal exposure were analyzed within a unique continuous variable counting the number of months of bilingual exposure along the studied perinatal period (i.e., from the third trimester of pregnancy up to one year post-birth; Austin, 2014; Chiera et al., 2020; Marriott et al., 2019).

Bilingual exposure in the sample was characterized by the combination of Spanish and other language, being for most of the cases the Spanish-Catalan combination (89.3%). Other languages heard by infants were Bulgarian, English, Galego, Guarani, Moroccan Arabic and Portuguese (see more details in Table 1). Languages composing monolingual environments in the sample were either Spanish (88.2%) or Catalan (11.8%).

Table 1

Languages heard by infants from the third trimester of pregnancy to 12 months of age.

Languages	N	%
Spanish	15	20.5
Catalan	2	2.7
Spanish-Catalan	49	67.1
Spanish-Other	7	9.7
Bulgarian	1	1.4
English	1	1.4
Galego	1	1.4
Guarani	2	2.7
Moroccan Arabic	1	1.4
Portugal	1	1.4

206 **2.3 Stimulus**

207 Neural responses were obtained to a 250 ms two-vowel /oa/ speech stimulus with a
208 rising pitch ending, previously designed in our laboratory (for a detailed description, see
209 Arenillas-Alcón et al., 2021). Three different sections can be differentiated in the
210 stimulus according to its F_0 and F_1: the /o/ section (from 10 to 80 ms; F_0 = 113 Hz; F_1 =
211 452 Hz), the /a/ steady section (from 90 to 160 ms; F_0 = 113 Hz; F_1 = 678 Hz) and the
212 /a/ rising section (from 160 to 250 ms; F_0 = 113-154 Hz; F_1 = 678 Hz). Both steady
213 sections of the stimulus (/o/ and /a/ steady sections) were considered together for the
214 analysis of the F_0 encoding, giving rise to the stimulus steady section (from 10 to 160
215 ms; F_0 = 113 Hz).

216 The specific vowels' F_1 were chosen as those belong to the prototypical phonetic
217 repertoire in both Spanish and Catalan languages (Alarcos Llorach, 1965; Martí i Roca,
218 1986). The stimulus was presented at a rate of 3.39 Hz and an intensity of 60 dB SPL to
219 the right ear. It was delivered in alternating polarities through an earphone connected to
220 a Flexicoupler® disposable adaptor (Natus Medical Incorporated, San Carlos, CA).

221 **2.4 Procedure and data acquisition**

222 Neonatal FFR responses were recorded while the babies were sleeping in their crib at
223 the hospital room. FFR sessions at six and twelve months of age were conducted at a
224 hospital dispensary while ensuring the infant remained either asleep or as calm as
225 possible, aiming to guarantee the highest quality of data. The recording sessions had a
226 total mean duration of around 30 minutes, including 5 minutes of preparation time, 20
227 minutes of recording (4 /oa/ blocks × 1000 sweeps × 295 ms stimulus-onset
228 asynchrony), and up to 5 minutes of additional time for the rejected sweeps.

The speech stimulus was presented using a SmartEP platform connected to a Duet amplifier, which includes the cABR and Advanced Hearing Research modules (Intelligent Hearing Systems, Miami, Fl, USA). Neural responses were recorded using three disposable Ag/AgCl electrodes placed in a vertical montage (active electrode located at Fpz, ground at the forehead and reference at the right mastoid), keeping impedances below 10 kΩ for all electrodes. The continuous FFR signal acquisition was completed at a sampling rate of 13333 Hz utilizing an online bandpass filter to eliminate frequencies outside the 30 to 1500 Hz range. EEG online data was epoched from -40.95 (pre-stimulus period) to 249.975 ms, automatically excluding any sweep with voltage values exceeding ± 30 µV.

2.5 Data processing

Acquired FFRs were bandpass filtered from 80 to 1500 Hz. To emphasize the FFR components associated to the speech stimulus envelope (FFR_{ENV}) and to diminish putative cochlear microphonics, neural responses to alternating polarities were averaged [(Condensation + Rarefaction)/2]. To assess the neural encoding of the stimulus' F_1, and minimizing the envelope related neural activity (Aiken & Picton, 2008; Krizman & Kraus, 2019), the FFR temporal fine structure (FFR_{TFS}) was obtained by subtracting neural responses to the two opposite polarities [(Rarefaction–Condensation)/2].

FFR parameters were estimated using custom scripts from Matlab R2019b (The MathWorks Inc., 2019), previously developed in our laboratory and used in former similar studies (Arenillas-Alcón et al., 2021; Ribas-Prats et al., 2019). A detailed description can be found below for the three FFR parameters separately extracted and tested for the different stimulus features of interest.

Spectral amplitude. Spectral amplitude (in nV) was obtained as an indicator of the neural-phase locking magnitude at the frequency of interest (F_0, 113 Hz; /o/ F_1, 452 Hz; /a/ F_1, 678 Hz) (Arenillas-Alcón et al., 2021; Ribas-Prats et al., 2019; White-Schwoch et al., 2015b). It was calculated by applying the Fast Fourier Transform (FFT; Cooley & Tukey, 1965) to the neural response. Spectral amplitude was defined as the mean amplitude within a ±5 Hz window centered at the frequency peak of interest. Spectral amplitude at F_0 was obtained from the FFR_{ENV} corresponding to the stimulus steady section (10 to 160 ms) to quantify voice pitch encoding of the speech-sound stimulus. Spectral amplitudes at the vowels' F_1 frequencies were retrieved separately from the FFR_{TFS} corresponding to the /o/ section (10 to 80 ms) and the /a/ steady section (90 to 160 ms).

Pitch error. Pitch error (in Hz) was extracted from the FFR_{ENV} as a measure of pitch encoding accuracy for the F_0 contour along the two /a/ sections of the stimulus (i.e., /a/ steady section and /a/ rising section). It was computed as an average of the absolute Euclidian distance between the stimulus and response F_0 from each bin separately for the two sections mentioned.

2.6 Statistical analysis

Statistical analyses were performed using Jamovi 2.4.11 (The Jamovi Project, 2024). To explore the effects of perinatal bilingual environment exposure and sex on the developmental trajectory of neural encoding of speech, linear mixed effects models were constructed separately for each FFR parameter according to our hypothesis: spectral amplitude (at 113 Hz, 452 Hz and 678 Hz) and pitch error (during the /a/ steady and /a/ rising). Normality was assessed with Kolmogorov-Smirnov test and a natural logarithm (ln) transformation was applied to spectral amplitude dependent variables, as

those did not meet such assumption. Five different models were created to explore the trajectory of neural encoding of speech sound characteristics, one per each dependent variable, as follows:

FFR parameter ~ age + sex + bilingual exposure + age*sex + age*bilingual exposure + (1|subject)

Individual tested models predicted each FFR value as a function of age (birth, six and twelve months) and sex (male, female) and bilingual perinatal exposure (as a covariate, ranging from 0 to 15 months of exposure). The models also included the interaction effect of age per sex, and age per bilingual exposure. A by-subject random intercept was included in the models to account for infants' repeated measures.

A trend analysis was performed within each separated model by coding the age variable with polynomial contrasts, which describe possible trends in the means (i.e., shape of the age-dependent trend). The polynomial regression was thus applied to depict the relationship between the FFR parameters and age to find the best way to draw a line through the data points. After a significant result for the omnibus test of fixed effects, post-hoc ANOVA or multiple comparison with Bonferroni adjustments were conducted to further inspect the given result. Only Bonferroni-corrected p-values are reported in the results section. Normality of residuals was met for each independent model, which was checked using Kolmogorov-Smirnov test.

3. Results

Clear FFRs were elicited across each developmental stage (i.e., at birth, six months and twelve months) in both female and male infants. These neural responses are illustrated in Fig.1, as FFR waveforms and corresponding spectral representations. As it can be

observed in the figure, spectral peaks are present at F_0 across ages, and for the stimulus F_1 emerging from 6 months onwards.

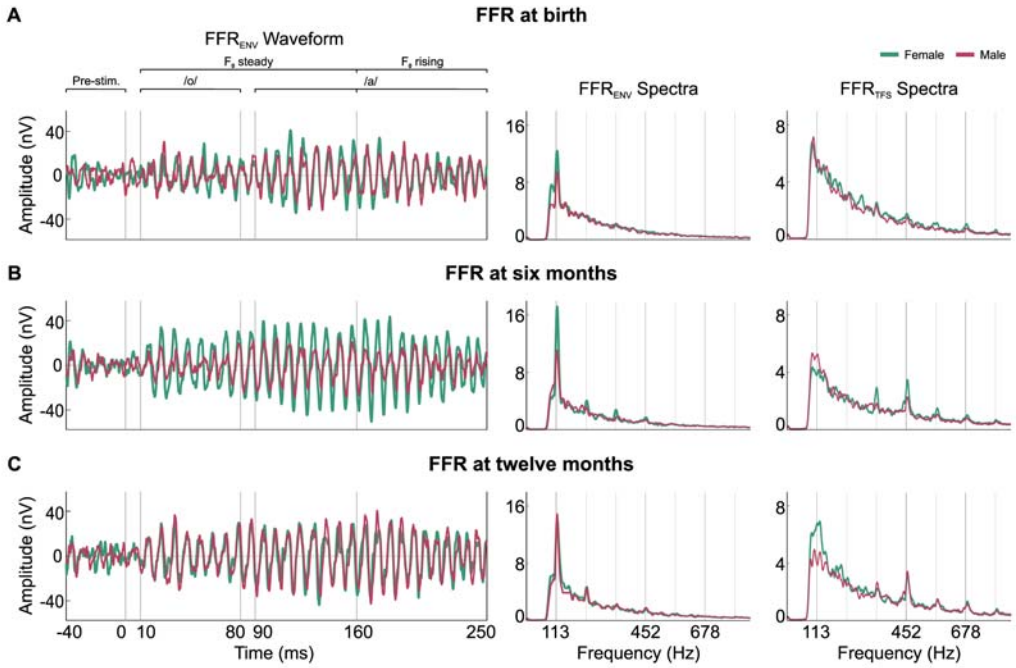

Fig. 1. FFRs from 38 female (in green) and 35 male infants (in red) recorded at each developmental stage: (**A**) at birth, (**B**) at six months and (**C**) at twelve months. The left column displays grand-averaged FFR_{ENV} waveforms in the time domain for each age group. The middle and right columns illustrate the amplitude spectra of FFR_{ENV} and FFR_{TFS}, respectively, both extracted from the steady section of the stimulus (10–160 ms). Remarkably, a clear sex difference in F_0 encoding emerges at six months of age, with females displaying larger amplitudes than males.

3.1 Voice pitch encoding

Spectral amplitude at stimulus F_0. The model fit was statistically significant ($X^2(9)$ = 37.544; R^2 = .275; p < .001). The regression results for the model indicated a main effect of sex (β = -.242; t(70.6) = -2.312; p = .024), with general higher spectral amplitudes shown by female infants (M = .013 ± .008) in comparison to their male peers (M = .01 ± .006; see Fig. 2A). The interaction effect between age and sex was found to be a significant predictor ($F_{(2,140.3)}$ = 3.15; p = .046), with higher values for female in comparison to male infants at the age of six months (t(199) = 3.36; p = .014). Moreover,

the interaction between the quadratic effects of age and sex was found as a significant predictor of the spectral amplitude at 113 Hz (β = .347; t(140.2) = 2.43; p = .016). Simple slopes analysis revealed that the quadratic trajectory of spectral amplitude as a function of age was only present for female infants (β = -.237; t(156) = -2.01; p = .047). The interaction effect between age and bilingual exposure was also significant ($F_{(2,173.6)}$ = 8.19; p < .001; see Fig. 2A). Simple slope analysis revealed a negative effect of bilingual exposure on spectral amplitudes at six months (β = -.051; t(209.4) = -2.42; p = .017), along with a positive effect at twelve months (β = .043; t(209.9) = 3.27; p = .001). The quadratic effect of age per bilingual exposure interaction was also found to be significant (β = .062; t(161.1) = 2.33; p = .021). Simple slopes analysis revealed that only for monolingual infants (i.e., none-exposed to bilingualism) a significant quadratic effect of age was predicted on spectral amplitude at 113 Hz (β = -.340; t(142.1) = -3.06; p = .003).

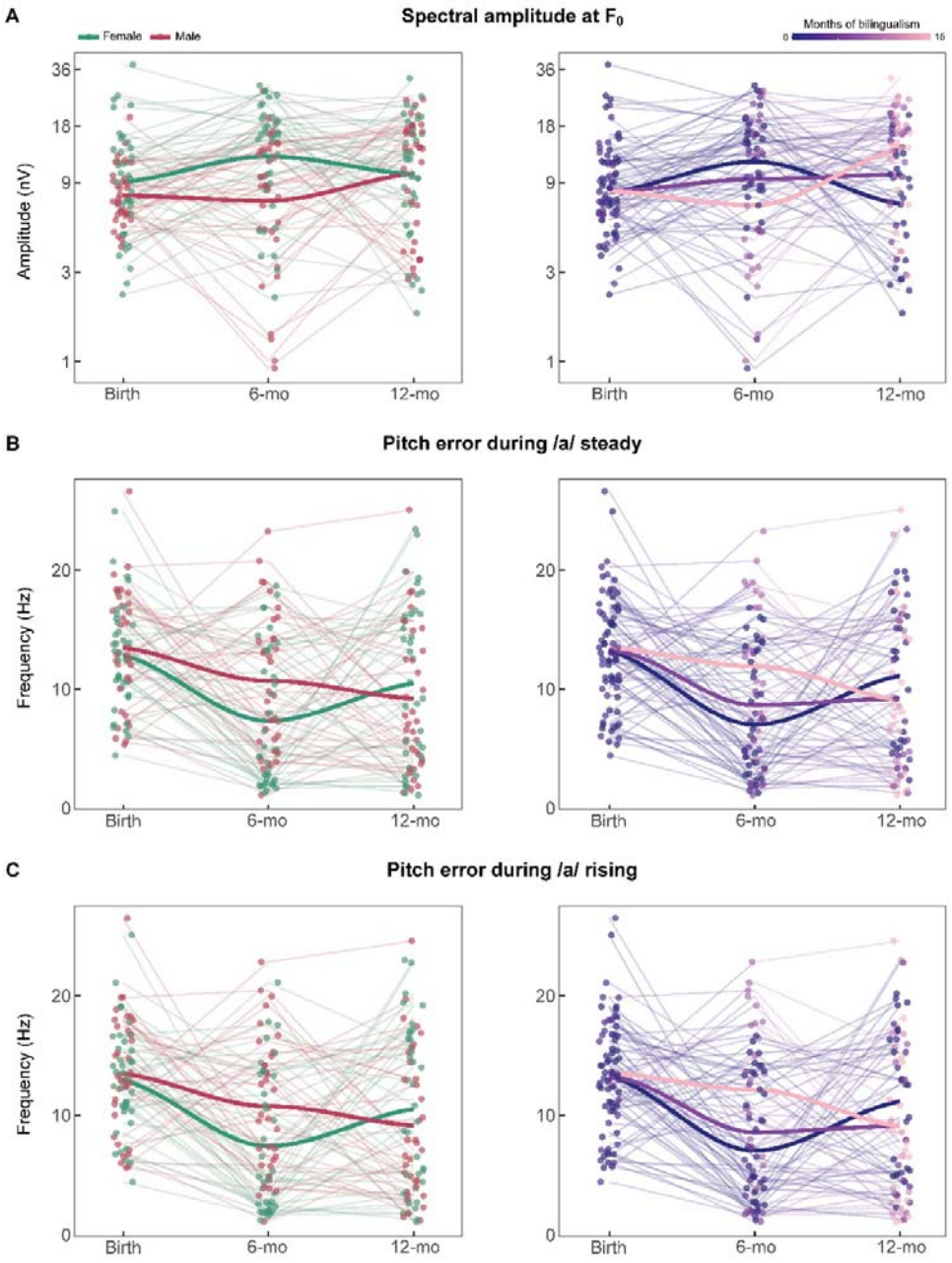

Fig. 2. Predicted developmental trajectories of (**A**) spectral amplitudes at F_0 and (**B**) pitch error during both /a/ steady and (**C**) rising sections of the stimulus across the three developmental stages: at birth, six months (6-mo) and twelve months (12-mo). Solid lines illustrate the predicted trajectories based on sex (left panel: female in green, male in red) and bilingual exposure (right panel: no exposure in dark blue, median exposure in purple, maximum exposure in pink). (**A**) Each data point represents the log-transformed spectral amplitudes of the longitudinally tested infants to account for skewness. For interpretability, the y-axis displays the corresponding real spectral amplitude values. Data points displayed in (**B**) and (**C**) represent the non-transformed pitch error values corresponding to each tested infant.

Pitch error during the /a/ steady section. The model fit was statistically significant ($X^2(9) = 38.618$; $R^2 = .232$; $p < .001$). The regression results for the model indicated a main effect of age ($F_{(2,176.9)} = 3.58$; $p = .030$), with higher values at birth ($M = 13.25 \pm 1.43$) in comparison to six months of age ($M = 9.19 \pm .66$; $t(194.1) = 2.64$; $p = .027$) and depicting a significant quadratic trajectory ($\beta = 2.09$; $t(162.9) = 2.55$; $p = .012$). The interaction between the quadratic effect of age and sex was found as a significant predictor of pitch error during the /a/ steady section ($\beta = -2.826$; $t(140.5) = -2.25$; $p = .026$; see Fig. 2B), with simple slopes analysis revealing a quadratic trajectory only significantly present for female infants ($\beta = 3.504$; $t(156.8) = 3.39$; $p < .001$). The interaction effect between age and bilingual exposure was also found to be a significant predictor ($F_{(2,175.1)} = 4.31$; $p = .015$; see Fig. 2B). Post-hoc estimates revealed higher pitch error values as a function of bilingual exposure at six months of age ($\beta = .470$; $t(209.7) = 2.62$; $p = .009$).

Pitch error during the /a/ rising section. The model fit was statistically significant ($X^2(9) = 39.642$; $R^2 = .241$; $p < .001$). The regression results for the model indicated a main effect of age ($F_{(2,176.9)} = 3.51$; $p = .032$), with higher values at birth ($M = 13.28 \pm 1.42$) in comparison to six months of age ($M = 9.25 \pm .66$; $t(194) = 2.62$; $p = .028$) and depicting a quadratic effect of age as a significant predictor of pitch error during the /a/ rising section ($\beta = 2.04$; $t(162.7) = 2.50$; $p = .013$). The interaction between age and sex was found as a significant predictor ($F_{(2,140.6)} = 3.14$; $p = .046$). Post-hoc comparisons revealed higher values for female infants at six months in comparison to male neonates ($t(209.8) = 3.35$; $p = .014$). The interaction between the quadratic effects of age and sex was also found as a significant predictor ($\beta = -2.871$; $t(140.5) = -2.30$; $p = .023$; see Fig. 2C). Simple slopes analysis revealed that the quadratic trajectory of pitch error as a function of age was only present for female infants ($\beta = 3.474$; $t(156.7) = 3.38$; $p <$

.001). The interaction effect between age and bilingual exposure was also found to be a significant predictor ($F_{(2,175)}$ = 4.72; p = .010; see Fig. 2C). Post-hoc estimates revealed higher pitch error values as a function of bilingual exposure at six months of age (β = .491; t(209.7) = 2.75; p = .006).

3.2 Formant structure encoding

Spectral amplitude at /o/ vowel F_1. Model fit was statistically significant (X^2(9) = 30.512; R^2 = .211; p < .001). The regression results for the model indicated a main effect of age ($F_{(2,176.6)}$ = 4.77; p = .01), with lower values at birth (M = .003 ± .003) in comparison to both six months (M = .004 ± .004; t(193.8) = -2.93; p = .011) and twelve months of age (M = .004 ± .004; t(208.2) = -2.95; p = .010). Both a linear (β = .526; t(208.2) = 2.96; p = .003) and a quadratic (β = -.276; t(162.2) = -2.15; p = .033) effect of age resulted as significant predictors of spectral amplitude at 452 Hz. The interaction between age and sex was found to a be significant predictor ($F_{(2,140.2)}$ = 6.15; p = .003; see Fig. 3A), with six-months old females showing higher spectral amplitudes in comparison to both male (t(210) = -3.27; p = .019) and female neonates (t(184) = -3.83; p = .003). Significantly higher spectral amplitudes were also depicted for twelve-months male infants in comparison to female neonates (t(204) = -3.23; p = .022). The interaction of age as following a quadratic trajectory by sex was found as a significant predictor (β = .684; t(140.0) = 3.48; p < .001), with post-hoc results showing a significant quadratic effect of age only for female participants (β = -.618; t(156) = -3.81; p < .001).

The interaction between age and bilingual exposure was also significant ($F_{(2,174.6)}$ = 3.41; p = .035; see Fig. 3A), although post-hoc estimates results did not reach statistical significance at any developmental stage. The linear effect of age per bilingual exposure

interaction was also found as a significant predictor (β = .115; t(199.3) = 2.26; p = .025), indicating that the linear trajectory of age on spectral amplitude at 452 Hz depends on the level of bilingual exposure. Simple slopes analysis revealed a predicted linear effect of age specifically for infants with medium level of bilingual exposure (7.5 months of exposure; β = .920; t(207.8) = 2.81; p = .005) and for those with maximum bilingual exposure (15 months of exposure; β = 1.780; t(204.7) = 2.56; p = .011).

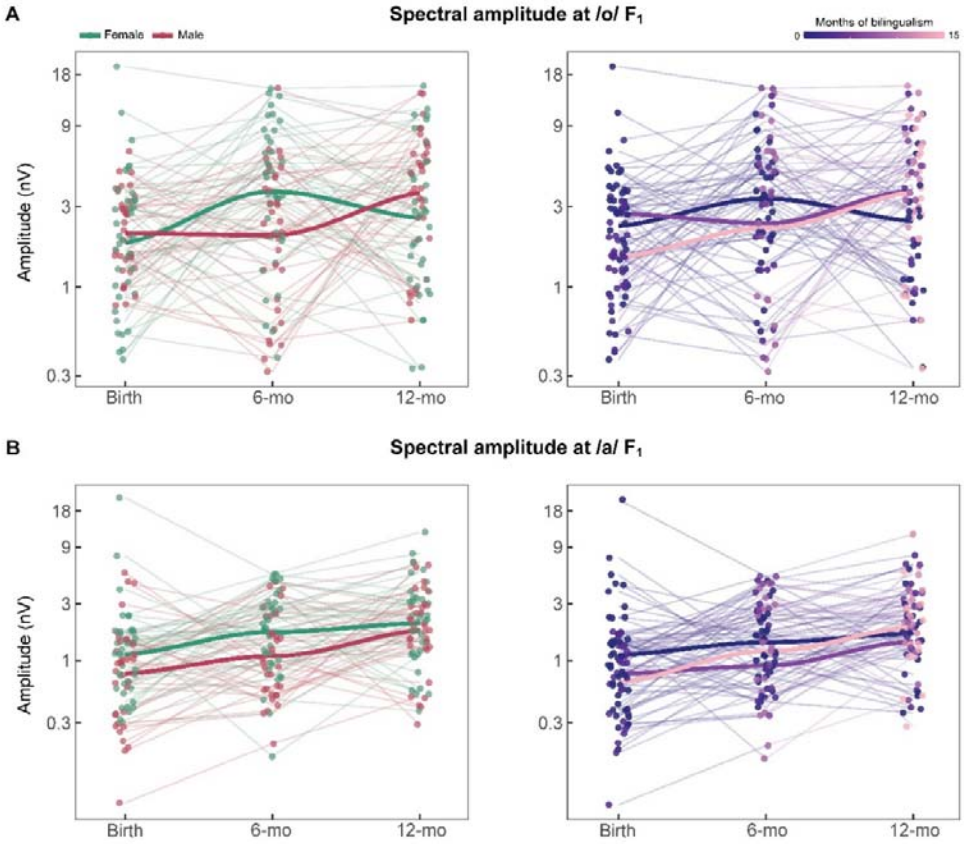

Fig. 3. Predicted developmental trajectories of neural encoding for (**A**) /o/ F_1 and (**B**) /a/ F_1 across the three developmental stages: at birth, six months (6-mo) and twelve months (12-mo). Each point represents the log-transformed amplitudes for each longitudinally tested infant to account for skewness. For interpretability, the y-axis displays the corresponding real spectral amplitude values. The solid lines represent the predicted trajectories according to sex (left panel: female in green, male in red) and bilingual exposure (right panel: no exposure in dark blue, median exposure in purple, maximum exposure in pink).

Spectral amplitude at /a/ vowel F_1. Model fit was statistically significant (X^2(9) = 47.423; R^2 = .323; p < .001). The regression results indicated a main effect of age

($F_{(2,176.7)}$ = 10.75; p < .001), with lower values at birth (M = .0015 ± .003) in comparison to both six months (M = .0018 ± .001; t(193.1) = -3.53; p = .002) and twelve months of age (M = .0025 ± .002; t(208.4) = -4.61; p < .001). Moreover, a linear effect of age was depicted as a significant predictor of spectral amplitude at 678 Hz (β = .769; t(208.4) = 4.61; p < .001). A main effect of sex was also discovered (β = -.309; t(70.9) = -2.28; p = .026; see Fig. 3B), with general higher values for female infants (M = .0022 ± .003) than their male peers (M = .0016 ± .001). The linear effect of age per bilingual exposure interaction was also found as a significant predictor (β = .111; t(196.2) = 2.36; p = .019; see Fig. 3B), specifically indicating that the linear trajectory of age on spectral amplitude at 678 Hz depends on the level of bilingual exposure. Simple slopes analysis revealed a predicted positive linear effect of age for all three contrasted levels of bilingual exposure: none exposed infants (β = .317; t(159.6) = 2.40; p = .018), infants exposed during 7.5 months (β = 1.151; t(206.9) = 3.75; p < .001), and infants exposed during 15 months to bilingual exposure (β = 1.986; t(202.8) = 3.07; p = .002).

4. Discussion

The present study was set to investigate the distinct trajectories in the neural encoding of speech sound features across the first year of infant development, with a focus on the influences of sex and perinatal bilingual exposure. To that aim, we inspected FFR neural responses to a two-vowel /oa/ syllable at birth, six months, and twelve months of age. We then modeled the neural encoding of both pitch and formant structure over time, analyzing variations according to bilingualism and sex. Our findings provide new insights into how sex and early bilingual exposure shape the neural encoding of speech sounds in infancy, with potential implications for understanding the individual variability in early language acquisition.

Our results reveal a significant maturation of neural encoding for both voice pitch and formant structure of speech during the first six months of life, followed by a stabilization during the second half of the year. Notably, different developmental trajectories were observed for each of the different speech features of interest. While the encoding of both steady and rising F_0 contours followed a quadratic trajectory, the encoding of both vowels' F_1 exhibited a linear progression. Interestingly, the encoding of the /o/ F_1 frequency fit both linear and quadratic models, suggesting a more complex developmental pattern. These divergent trajectories may reflect differences related to the development of low- and high-frequency acoustic information processing, paralleling the spectrally ascendant developmental pattern of the auditory system (Graven & Browne, 2008). Accordingly, neural attunement to low frequency acoustic content initiates earlier, being the period from 25 gestational weeks to six postnatal months the most critical for the neurosensory development of the auditory system. This aligns with the earlier availability of low-frequency acoustic signals accessible to the fetus during the prenatal period (Hepper & Shahidullah, 1994; Voegtline et al., 2013) and is supported by previous research demonstrating robust pitch encoding already at birth (Arenillas-Alcón et al., 2021; Jeng et al., 2011). Intriguingly, although our findings did not reveal significant age-related changes in spectral amplitudes at F_0, we did identify marked improvements in the neural tracking of both steady and rising pitch contours within the first six months. These results may help clarify inconsistencies in previous research on infant age-related changes in pitch encoding, which may stem from subtle variations in the features examined (Anderson et al., 2015; Jeng et al., 2010; Puertollano et al., 2024; Ribas-Prats et al., 2023b; Van Dyke et al., 2017).

On the contrary, the neural encoding of F_1 components has been documented to experience significant enhancement already in the first postnatal month (Ribas-Prats

et al., 2023b), suggesting the rapid neural adaptation to novel frequencies that become significantly more available after birth. Our results corroborate previous research demonstrating further refinement of F_1 neural encoding during the first six months of life (Ribas-Prats et al., 2023b) and its stabilized development up to the age of twelve months (Puertollano et al., 2024), but further extend these findings by revealing a linear maturational pattern throughout the first year of life. This underscores the early development of neural mechanisms crucial for establishing a native language's sound map by six months, thereby facilitating native phoneme identification and discrimination (Kuhl, 1991, 2004, 2010; Kuhl et al., 1992).

A complementary explanation for this early maturation pattern lies in the constraints imposed by neuronal development, as shown by the evolution of electrophysiological brain activity in early infancy. Fetal and neonatal brain activity is primarily characterized by slow-wave oscillations that match the slow prosodic modulations found in speech. By around six months of age, faster neuronal oscillations that can phase-lock to phoneme-rate amplitude modulations emerge (Anderson & Perone, 2018; Le Van Quyen et al., 2006; Xu et al., 2011; for a review see Menn et al., 2023), enabling infants to encode higher-frequency speech components and build a repertoire of native phonemes (Kuhl, 2004). Neural encoding of phonetic features becomes robust by seven months of age and shows no further enhancement up to the age of eleven months (Di Liberto et al., 2023). Similarly, our findings highlight the first six months as a critical period, when the neural system increasingly attunes to the spectro-temporal features of the acoustic environment along the auditory pathway, setting the stage for subsequent phonetic learning (Werker & Hensch, 2015; Zhao et al., 2022).

There is a vast body of literature emphasizing the complex interplay between maturational and experiential influences on speech development (for a review see

Werker & Hensch, 2015). Evidence for a sensitive period for phonetic attunement occurring during the first twelve months of life comes from diverse biological and environmental contexts. While studies on infants born prematurely emphasize the relevance of maturational processes in speech perception development (Peña et al., 2010, 2012), research into acoustic deprivation due to infant deafness underscores the critical role of sensory input in driving acoustic-related neural plasticity during the first year of life (Faulkner & Pisoni, 2013; Kral & Sharma, 2012). A particular acoustic environment is that related to bilingual experience, which has been previously proposed to modulate the onset and duration of the sensitive period for phonetic learning (Best et al., 2016; Garcia-Sierra et al., 2011; Werker et al., 2009; Werker & Hensch, 2015). This extended sensitive period likely offers bilingual infants additional time to attune to the acoustic and phonological features of both languages. Our findings support this proposal by underscoring the moderating influence of bilingualism on the development of neural mechanisms involved in pitch and formant structure encoding, both of which are essential for speech and language acquisition.

We observed a negative impact of bilingual exposure on voice pitch encoding at six months, as reflected by lower spectral amplitudes at F_0 and higher pitch error values. This trend reversed by twelve months, with bilingual exposure predicting higher spectral amplitudes at F_0. This U-shaped pattern could reflect an initial struggle to attune to speech sounds, related to a more complex acoustic environment. Notably, immature neural responses to phonemic contrasts during the early months of life do not necessarily predict poorer language outcomes. Instead, they seem to facilitate latter attunement, leading to faster maturation rates and stronger responses later in development that are associated to enhanced language outcomes (García-Sierra et al., 2021; Schaadt et al., 2015, 2023; Werwach et al., 2022). In contrast, monolingual

infants in our sample followed an inverted U-shaped trajectory for F_0 encoding, with spectral amplitudes increasing from birth to six months and then declining between six and twelve months. These opposite trajectories in F_0 encoding depending on bilingual experience parallel those depicted for phonetic contrast discrimination during the second half of the first infant year (Byers□Heinlein & Fennell, 2014). F_0 variability may serve as a salient perceptual attribute that facilitates language separation for bilingual infants (Liu & Kager, 2017).

Bilingual experience further affected the maturation of formant structure encoding, with distinct effects on each vowel's F_1 frequencies. Specifically, infants with over seven months of total bilingual exposure showed linear growth in spectral amplitudes for /o/ F_1 across the first year, whereas this linear effect of age was not significant for monolingual infants. In contrast, neural encoding of /a/ F_1 followed a linear trajectory regardless of the amount of bilingual exposure. Our findings suggest a stronger influence of bilingual exposure in lower versus higher frequencies during early infant ages that may be related to the previously mentioned spectrally ascendant pattern of development (Graven & Browne, 2008). However, although describing distinct developmental trajectories for the encoding of pitch and formant structure, our results demonstrate that bilingual exposure positively impacts the neural encoding of both speech features at the age of twelve months. We thus provide evidence for previous literature hypothesizing a heightened acoustic sensitivity in bilingual infants manifesting near the end of the perceptual reorganization process (Liu & Kager, 2015, 2017), by specifically signaling distinct neural attunement along the auditory pathway associated to early bilingual exposure. Additionally, our results complement previous research on the effects of prenatal bilingual exposure in neural encoding of speech

sounds (Gorina-Careta et al., 2024) by extending the scope to postnatal development throughout the first year of life.

Our findings further underscore a significant influence of sex on the neural speech encoding in infants. Female infants exhibited higher overall spectral amplitudes at the stimulus F_0, indicating superior voice pitch neural phase-locking throughout the first year compared to males. Additionally, females followed a distinct quadratic developmental trajectory for pitch encoding, surpassing male spectral amplitudes at F_0 by six months and then declining closer to male values by twelve months. A similar quadratic pattern was observed for females in the encoding of /o/ F_1, marked by significant improvements during the first six months of life. Female infants also displayed overall higher amplitudes at /a/ F_1 across the first year. These results extend those of Krizman et al. (2019, 2020) by revealing sex differences in auditory processing emerging in infancy, well before the adolescent differences they documented.

These sex-specific developmental patterns highlight early differences in neural encoding of speech-acoustic features between male and female infants during the first year of life. Our results align with previous research reporting sex differences in early speech encoding and acquisition, including disparities in the maturation of involved brain areas (Alexopoulos et al., 2022), infant phonological discrimination (Friederici et al., 2008), the onset and rate of word production (Dailey & Bergelson, 2023), and the frequency of speech-like vocalizations before first words (Sung et al., 2013). A growing body of research links infants' hormone levels to these early developmental differences (Lust et al., 2010; Lutchmaya et al., 2001; Wermke et al., 2014). For example, sex hormone levels have been linked to infant phonological discrimination (Friederici et al., 2008), articulatory skills (Quast et al., 2016), and later language abilities in childhood (Hollier et al., 2013; Schaadt et al., 2015).

Another factor potentially contributing to these differences is the related to caregivers' speech input. Studies suggest that caregivers use higher pitch and a greater pitch range when speaking to female infants compared to males, with this difference growing over time (Kitamura et al., 2001; Kitamura & Burnham, 2003). The duration of speech input also shows sex-specific patterns, with speech directed to male infants decreasing during the first year of life, while increasing for female infants (Sung et al., 2013). Furthermore, caregivers tend to talk more to infants who have started talking (Dailey & Bergelson, 2023), which could reinforce sex differences in speech abilities given that females often begin speaking earlier than males (Bornstein et al., 2004; Eriksson et al., 2012; Fenson et al., 1994). These biological and social factors likely interact, shaping the sex-related differences in the developmental trajectory of neural speech encoding observed in our results.

Although there is a large research community exploring speech perception in infants, using both behavioral and neurophysiological measures (Byers-Heinlein et al., 2010; Hervé et al., 2022; Kuhl et al., 2003, 2006; Kujala et al., 2023), the use of the FFR provides a direct neural measurement of the auditory hierarchy that reflect the attunement to the spectral and temporal features of speech (Coffey et al., 2016; Gorina-Careta et al., 2021; Krizman & Kraus, 2019; Skoe & Kraus, 2010). By utilizing the FFR, our results highlight the pivotal importance of the first six months in neural development for speech encoding. Thereby, future studies should incorporate more frequent time-point measurements to gain a comprehensive understanding of this early period. We observed distinct developmental trajectories in the neural encoding of speech features, influenced by both sex and perinatal bilingual exposure. Consistently incorporating these factors into research on early speech and language development is

crucial for capturing an accurate depiction of these early processes, enhancing replicability and deepening our understanding of infant development.

5. Conclusion

The present study provides novel insights into the distinct developmental trajectories of neural speech encoding during the first year of life, influenced by both sex and perinatal bilingual exposure. By examining longitudinally FFR neural responses to a two-vowel stimulus, we revealed a significant maturation of pitch and formant structure encoding throughout the first six months of life, without further maturation up to the age of twelve months. These findings emphasize the first six months as a critical period for neural adaptation to the acoustic environment, contributing to early phonetic learning and language acquisition. The moderating effects of bilingual exposure on voice pitch and formant encoding, as well as the sex-specific differences observed, underscore the complexity and individual variability related to early auditory and speech perception development. These results not only extend previous research but also contribute to a deeper understanding of the neural foundations of early language acquisition. Future studies incorporating more frequent developmental assessments could help refine our understanding of this sensitive period.

5. References

Abrams, R. M., Gerhardt, K. J., Huang, X., Peters, A. J. M., & Langford, R. G. (2000). Musical experiences of the unborn baby. *Journal of Sound and Vibration*, *231*(1), 253-258. https://doi.org/10.1006/jsvi.1999.2605

Aiken, S. J., & Picton, T. W. (2008). Envelope and spectral frequency-following responses to vowel sounds. *Hearing Research*, *245*(1-2), 35-47. https://doi.org/10.1016/j.heares.2008.08.004

Alarcos Llorach, E. (1965). *Fonología española [Spanish phonology]*. Gredos.

Alexopoulos, J., Giordano, V., Doering, S., Seidl, R., Benavides-Varela, S., Russwurm, M., Greenwood, S., Berger, A., & Bartha-Doering, L. (2022). Sex differences in neural processing of speech in neonates. *Cortex*, *157*, 117-128. https://doi.org/10.1016/j.cortex.2022.09.007

Anderson, A. J., & Perone, S. (2018). Developmental change in the resting state electroencephalogram: Insights into cognition and the brain. *Brain and Cognition*, *126*, 40-52. https://doi.org/10.1016/j.bandc.2018.08.001

Anderson, S., Parbery-Clark, A., White-Schwoch, T., & Kraus, N. (2015). Development of subcortical speech representation in human infants. *The Journal of the Acoustical Society of America*, *137*(6), 3346-3355. https://doi.org/10.1121/1.4921032

Arenillas-Alcón, S., Costa-Faidella, J., Ribas-Prats, T., Gómez-Roig, M. D., & Escera, C. (2021). Neural encoding of voice pitch and formant structure at birth as revealed by frequency-following responses. *Scientific Reports*, *11*(1), 6660. https://doi.org/10.1038/s41598-021-85799-x

Arenillas□Alcón, S., Ribas□Prats, T., Puertollano, M., Mondéjar□Segovia, A., Gómez□Roig, M. D., Costa□Faidella, J., & Escera, C. (2023). Prenatal daily

musical exposure is associated with enhanced neural representation of speech fundamental frequency: Evidence from neonatal frequency following responses. *Developmental Science*, *26*(5), e13362. https://doi.org/10.1111/desc.13362

Austin, M. P. (2014). Marcé International Society position statement on psychosocial assessment and depression screening in perinatal women. *Best Practice & Research Clinical Obstetrics & Gynaecology*, *28*(1), 179-187. https://doi.org/10.1016/j.bpobgyn.2013.08.016

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and subcortical auditory function. *Cerebral Cortex*, *19*(11), 2699-2707. https://doi.org/10.1093/cercor/bhp024

Banai, K., Nicol, T., Zecker, S. G., & Kraus, N. (2005). Brainstem Timing: Implications for Cortical Processing and Literacy. *The Journal of Neuroscience*, *25*(43), 9850-9857. https://doi.org/10.1523/JNEUROSCI.2373-05.2005

Best, C., Goldstein, L. M., Nam, H., & Tyler, M. D. (2016). Articulating What Infants Attune to in Native Speech. *Ecological Psychology*, *28*(4), 216-261. https://doi.org/10.1080/10407413.2016.1230372

Best, C., & McRoberts, G. W. (2003). Infant Perception of Non-Native Consonant Contrasts that Adults Assimilate in Different Ways. *Language and Speech*, *46*(2-3), 183-216. https://doi.org/10.1177/00238309030460020701

Bornstein, M. H., Cote, L. R., Maital, S., Painter, K., Park, S.-Y., Pascual, L., Pêcheux, M.-G., Ruel, J., Venuti, P., & Vyt, A. (2004). Cross-Linguistic Analysis of Vocabulary in Young Children: Spanish, Dutch, French, Hebrew, Italian, Korean, and American English. *Child Development*, *75*(4), 1115-1139. https://doi.org/10.1111/j.1467-8624.2004.00729.x

Byers-Heinlein, K., Burns, T. C., & Werker, J. F. (2010). The Roots of Bilingualism in Newborns. *Psychological Science*, *21*(3), 343-348. https://doi.org/10.1177/0956797609360758

Byers□Heinlein, K., & Fennell, C. T. (2014). Perceptual narrowing in the context of increased variation: Insights from bilingual infants. *Developmental Psychobiology*, *56*(2), 274-291. https://doi.org/10.1002/dev.21167

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience*, *1*(5), 351-353. https://doi.org/10.1038/1561

Coffey, E. B. J., Herholz, S. C., Chepesiuk, A. M. P., Baillet, S., & Zatorre, R. J. (2016). Cortical contributions to the auditory frequency-following response revealed by MEG. *Nature Communications*, *7*(1), 11070. https://doi.org/10.1038/ncomms11070

Coffey, E. B. J., Nicol, T., White-Schwoch, T., Chandrasekaran, B., Krizman, J., Skoe, E., Zatorre, R. J., & Kraus, N. (2019). Evolving perspectives on the sources of the frequency-following response. *Nature Communications*, *10*(1), 5036. https://doi.org/10.1038/s41467-019-13003-w

Cooley, J. W., & Tukey, J. W. (1965). An algorithm for the machine calculation of complex Fourier series. *Mathematics of Computation*, *19*(90), 297-301. https://doi.org/10.1090/S0025-5718-1965-0178586-1

Cunningham, J., Nicol, T., Zecker, S. G., Bradlow, A., & Kraus, N. (2001). Neurobiologic responses to speech in noise in children with learning problems: Deficits and strategies for improvement. *Clinical Neurophysiology*, *112*(5), 758-767. https://doi.org/10.1016/S1388-2457(01)00465-5

672 Dailey, S., & Bergelson, E. (2023). Talking to talkers: Infants' talk status, but not their
673 gender, is related to language input. *Child Development*, *94*(2), 478-496.
674 https://doi.org/10.1111/cdev.13872
675 DeAnda, S., Bosch, L., Poulin-Dubois, D., Zesiger, P., & Friend, M. (2016). The
676 Language Exposure Assessment Tool: Quantifying Language Exposure in
677 Infants and Children. *Journal of Speech, Language, and Hearing Research*,
678 *59*(6), 1346-1356. https://doi.org/10.1044/2016_JSLHR-L-15-0234
679 DeCasper, A. J., & Fifer, W. P. (1980). Of Human Bonding: Newborns Prefer Their
680 Mothers' Voices. *Science*, *208*(4448), 1174-1176.
681 https://doi.org/10.1126/science.7375928
682 Di Liberto, G. M., Attaheri, A., Cantisani, G., Reilly, R. B., Ní Choisdealbha, Á.,
683 Rocha, S., Brusini, P., & Goswami, U. (2023). Emergence of the cortical
684 encoding of phonetic features in the first year of life. *Nature Communications*,
685 *14*(1), 7789. https://doi.org/10.1038/s41467-023-43490-x
686 Draganova, R., Schollbach, A., Schleger, F., Braendle, J., Brucker, S., Abele, H.,
687 Kagan, K. O., Wallwiener, D., Fritsche, A., Eswaran, H., & Preissl, H. (2018).
688 Fetal auditory evoked responses to onset of amplitude modulated sounds. A fetal
689 magnetoencephalography (fMEG) study. *Hearing Research*, *363*, 70-77.
690 https://doi.org/10.1016/j.heares.2018.03.005
691 Eriksson, M., Marschik, P. B., Tulviste, T., Almgren, M., Pérez Pereira, M., Wehberg,
692 S., Marjanovič-Umek, L., Gayraud, F., Kovacevic, M., & Gallego, C. (2012).
693 Differences between girls and boys in emerging language skills: Evidence from
694 10 language communities. *British Journal of Developmental Psychology*, *30*(2),
695 326-343. https://doi.org/10.1111/j.2044-835X.2011.02042.x

696 Faulkner, K., & Pisoni, D. (2013). Some observations about cochlear implants:
697 Challenges and future directions. *Neuroscience Discovery*, *1*, 1-10.
698 https://doi.org/10.7243/2052-6946-1-9
699 Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., Pethick, S. J., Tomasello,
700 M., Mervis, C. B., & Stiles, J. (1994). Variability in Early Communicative
701 Development. *Monographs of the Society for Research in Child Development*,
702 *59*(5), i. https://doi.org/10.2307/1166093
703 Fernald, A., & Simon, T. (1984). Expanded intonation contours in mothers' speech to
704 newborns. *Developmental Psychology*, *20*(1), 104-113.
705 https://doi.org/10.1037/0012-1649.20.1.104
706 Figueras, F., & Gratacós, E. (2014). Update on the Diagnosis and Classification of Fetal
707 Growth Restriction and Proposal of a Stage-Based Management Protocol. *Fetal*
708 *Diagnosis and Therapy*, *36*(2), 86-98. https://doi.org/10.1159/000357592
709 Filippa, M., Kuhn, P., & Westrup, B. (Eds.). (2017). *Early Vocal Contact and Preterm*
710 *Infant Brain Development*. Springer International Publishing.
711 https://doi.org/10.1007/978-3-319-65077-7
712 Friederici, A. D., Pannekamp, A., Partsch, C.-J., Ulmen, U., Oehler, K., Schmutzler, R.,
713 & Hesse, V. (2008). Sex hormone testosterone affects language organization in
714 the infant brain. *NeuroReport*, *19*(3), 283-286.
715 https://doi.org/10.1097/WNR.0b013e3282f5105a
716 García-Sierra, A., Ramírez-Esparza, N., & Kuhl, P. K. (2016). Relationships between
717 quantity of language input and brain responses in bilingual and monolingual
718 infants. *International Journal of Psychophysiology*, *110*, 1-17.
719 https://doi.org/10.1016/j.ijpsycho.2016.10.004

García-Sierra, A., Ramírez-Esparza, N., Wig, N., & Robertson, D. (2021). Language learning as a function of infant directed speech (IDS) in Spanish: Testing neural commitment using the positive-MMR. *Brain and Language*, *212*, 104890. https://doi.org/10.1016/j.bandl.2020.104890

García-Sierra, A., Rivera-Gaxiola, M., Percaccio, C. R., Conboy, B. T., Romo, H., Klarman, L., Ortiz, S., & Kuhl, P. K. (2011). Bilingual language learning: An ERP study relating early brain responses to speech, language input, and later word production. *Journal of Phonetics*, *39*(4), 546-557. https://doi.org/10.1016/j.wocn.2011.07.002

Gerhardt, K. J., & Abrams, R. M. (1996). Fetal hearing: Characterization of the stimulus and response. *Seminars in Perinatology*, *20*(1), 11-20. https://doi.org/10.1016/S0146-0005(96)80053-X

Gerhardt, K. J., & Abrams, R. M. (2000). Fetal Exposures to Sound and Vibroacoustic Stimulation. *Journal of Perinatology*, *20*(S1), S21-S30. https://doi.org/10.1038/sj.jp.7200446

Gervain, J., & Mehler, J. (2010). Speech Perception and Language Acquisition in the First Year of Life. *Annual Review of Psychology*, *61*(1), 191-218. https://doi.org/10.1146/annurev.psych.093008.100408

Gorina-Careta, N., Arenillas-Alcón, S., Puertollano, M., Mondéjar-Segovia, A., Ijjou-Kadiri, S., Costa-Faidella, J., Gómez-Roig, M. D., & Escera, C. (2024). Exposure to bilingual or monolingual maternal speech during pregnancy affects the neurophysiological encoding of speech sounds in neonates differently. *Frontiers in Human Neuroscience*, *18*, 1379660. https://doi.org/10.3389/fnhum.2024.1379660

744 Gorina-Careta, N., Kurkela, J. L. O., Hämäläinen, J., Astikainen, P., & Escera, C.
745 (2021). Neural generators of the frequency-following response elicited to stimuli
746 of low and high frequency: A magnetoencephalographic (MEG) study.
747 *NeuroImage*, *231*, 117866. https://doi.org/10.1016/j.neuroimage.2021.117866
748 Gorina-Careta, N., Ribas-Prats, T., Arenillas-Alcón, S., Puertollano, M., Gómez-Roig,
749 M. D., & Escera, C. (2022). Neonatal Frequency-Following Responses: A
750 methodological framework for clinical applications. *Seminars in Hearing*,
751 *43*(03), 162-176. https://doi.org/10.1055/s-0042-1756162
752 Granier-Deferre, C., Bassereau, S., Ribeiro, A., Jacquet, A.-Y., & DeCasper, A. J.
753 (2011). A Melodic Contour Repeatedly Experienced by Human Near-Term
754 Fetuses Elicits a Profound Cardiac Reaction One Month after Birth. *PLoS ONE*,
755 *6*(2), e17304. https://doi.org/10.1371/journal.pone.0017304
756 Graven, S. N., & Browne, J. V. (2008). Auditory Development in the Fetus and Infant.
757 *Newborn and Infant Nursing Reviews*, *8*(4), 187-193.
758 https://doi.org/10.1053/j.nainr.2008.10.010
759 Hepper, P. G., & Shahidullah, B. S. (1994). Development of fetal hearing. *Archives of*
760 *Disease in Childhood - Fetal and Neonatal Edition*, *71*(2), F81-F87.
761 https://doi.org/10.1136/fn.71.2.F81
762 Hervé, E., Mento, G., Desnous, B., & François, C. (2022). Challenges and new
763 perspectives of developmental cognitive EEG studies. *NeuroImage*, *260*,
764 119508. https://doi.org/10.1016/j.neuroimage.2022.119508
765 Hollier, L. P., Mattes, E., Maybery, M. T., Keelan, J. A., Hickey, M., & Whitehouse, A.
766 J. O. (2013). The association between perinatal testosterone concentration and
767 early vocabulary development: A prospective cohort study. *Biological*
768 *Psychology*, *92*(2), 212-215. https://doi.org/10.1016/j.biopsycho.2012.10.016

769 Jeng, F.-C., Hu, J., Dickman, B., Montgomery-Reagan, K., Tong, M., Wu, G., & Lin,
770 C.-D. (2011). Cross-Linguistic Comparison of Frequency-Following Responses
771 to Voice Pitch in American and Chinese Neonates and Adults. *Ear & Hearing*,
772 *32*(6), 699-707. https://doi.org/10.1097/AUD.0b013e31821cc0df
773 Jeng, F.-C., Schnabel, E. A., Dickman, B. M., Hu, J., Li, X., Lin, C.-D., & Chung, H.-K.
774 (2010). Early Maturation of Frequency-Following Responses to Voice Pitch in
775 Infants with Normal Hearing. *Perceptual and Motor Skills*, *111*(3), 765-784.
776 https://doi.org/10.2466/10.22.24.PMS.111.6.765-784
777 Joint Committee on Infant Hearing. (2019). Year 2019 Position Statement: Principles
778 and Guidelines for Early Hearing Detection and Intervention Programs. *Journal*
779 *of Early Hearing Detection and Intervention*, *4*(2), 1-44.
780 https://doi.org/10.15142/FPTK-B748
781 Kitamura, C., & Burnham, D. (2003). Pitch and Communicative Intent in Mother's
782 Speech: Adjustments for Age and Sex in the First Year. *Infancy*, *4*(1), 85-110.
783 https://doi.org/10.1207/S15327078IN0401_5
784 Kitamura, C., Thanavishuth, C., Burnham, D., & Luksaneeyanawin, S. (2001).
785 Universality and specificity in infant-directed speech: Pitch modifications as a
786 function of infant age and sex in a tonal and non-tonal language. *Infant Behavior*
787 *and Development*, *24*(4), 372-392. https://doi.org/10.1016/S0163-
788 6383(02)00086-3
789 Kral, A., & Sharma, A. (2012). Developmental neuroplasticity after cochlear
790 implantation. *Trends in Neurosciences*, *35*(2), 111-122.
791 https://doi.org/10.1016/j.tins.2011.09.004

792 Krizman, J., Bonacina, S., & Kraus, N. (2019). Sex differences in subcortical auditory
793 processing emerge across development. *Hearing Research*, *380*, 166-174.
794 https://doi.org/10.1016/j.heares.2019.07.002
795 Krizman, J., Bonacina, S., & Kraus, N. (2020). Sex differences in subcortical auditory
796 processing only partially explain higher prevalence of language disorders in
797 males. *Hearing Research*, *398*, 108075.
798 https://doi.org/10.1016/j.heares.2020.108075
799 Krizman, J., & Kraus, N. (2019). Analyzing the FFR: A tutorial for decoding the
800 richness of auditory function. *Hearing Research*, *382*, 107779.
801 https://doi.org/10.1016/j.heares.2019.107779
802 Krizman, J., Slater, J., Skoe, E., Marian, V., & Kraus, N. (2015). Neural processing of
803 speech in children is influenced by extent of bilingual experience. *Neuroscience*
804 *Letters*, *585*, 48-53. https://doi.org/10.1016/j.neulet.2014.11.011
805 Kuhl, P. K. (1991). Human adults and human infants show a "perceptual magnet effect"
806 for the prototypes of speech categories, monkeys do not. *Perception &*
807 *Psychophysics*, *50*(2), 93-107. https://doi.org/10.3758/BF03212211
808 Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature*
809 *Reviews Neuroscience*, *5*(11), 831-843. https://doi.org/10.1038/nrn1533
810 Kuhl, P. K. (2010). Brain Mechanisms in Early Language Acquisition. *Neuron*, *67*(5),
811 713-727. https://doi.org/10.1016/j.neuron.2010.08.038
812 Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (2006).
813 Infants show a facilitation effect for native language phonetic perception
814 between 6 and 12 months. *Developmental Science*, *9*(2).
815 https://doi.org/10.1111/j.1467-7687.2006.00468.x

816 Kuhl, P. K., Tsao, F.-M., & Liu, H.-M. (2003). Foreign-language experience in infancy:
817 Effects of short-term exposure and social interaction on phonetic learning.
818 *Proceedings of the National Academy of Sciences*, *100*(15), 9096-9101.
819 https://doi.org/10.1073/pnas.1532872100
820 Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., & Lindblom, B. (1992).
821 Linguistic Experience Alters Phonetic Perception in Infants by 6 Months of Age.
822 *Science*, *255*(5044), 606-608. https://doi.org/10.1126/science.1736364
823 Kujala, T., Partanen, E., Virtala, P., & Winkler, I. (2023). Prerequisites of language
824 acquisition in the newborn brain. *Trends in Neurosciences*, *46*(9), 726-737.
825 https://doi.org/10.1016/j.tins.2023.05.011
826 Lavigne-Rebillard, M., & Bagger-Sjöbäck, D. (1992). Development of the human stria
827 vascularis. *Hearing Research*, *64*(1), 39-51. https://doi.org/10.1016/0378-
828 5955(92)90166-K
829 Le Van Quyen, M., Khalilov, I., & Ben-Ari, Y. (2006). The dark side of high-frequency
830 oscillations in the developing brain. *Trends in Neurosciences*, *29*(7), 419-427.
831 https://doi.org/10.1016/j.tins.2006.06.001
832 Liu, L., & Kager, R. (2015). Bilingual exposure influences infant VOT perception.
833 *Infant Behavior and Development*, *38*, 27-36.
834 https://doi.org/10.1016/j.infbeh.2014.12.004
835 Liu, L., & Kager, R. (2017). Perception of tones by bilingual infants learning non-tone
836 languages. *Bilingualism: Language and Cognition*, *20*(3), 561-575.
837 https://doi.org/10.1017/S1366728916000183
838 Lust, J. M., Geuze, R. H., Van de Beek, C., Cohen-Kettenis, P. T., Groothuis, A. G. G.,
839 & Bouma, A. (2010). Sex specific effect of prenatal testosterone on language

lateralization in children. *Neuropsychologia*, *48*(2), 536-540. https://doi.org/10.1016/j.neuropsychologia.2009.10.014

Lutchmaya, S., Baron-Cohen, S., & Raggatt, P. (2001). Foetal testosterone and vocabulary size in 18- and 24-month-old infants. *Infant Behavior and Development*, *24*(4), 418-424. https://doi.org/10.1016/S0163-6383(02)00087-5

Mariani, B., Nicoletti, G., Barzon, G., Barajas, M. C. O., Shukla, M., Guevara, R., Suweis, S. S., & Gervain, J. (2023). Prenatal experience with language shapes the brain. *Science Advances*, *9*(47), eadj3524. https://doi.org/10.1126/sciadv.adj3524

Martí i Roca, J. (1986). Paràmetres Acústics per a la Síntesi de Consonants Fricatives Catalanes [Acoustic parameters for Catalan fricative consonants' synthesis]. *Estudios de fonética experimental*, *2*, 151-193. https://raco.cat/index.php/EFE/article/view/144198

Martinez-Alvarez, A., Gervain, J., Koulaguina, E., Pons, F., & De Diego-Balaguer, R. (2023). Prosodic cues enhance infants' sensitivity to nonadjacent regularities. *Science Advances*, *9*(15), eade4083. https://doi.org/10.1126/sciadv.ade4083

Maye, J., Werker, J. F., & Gerken, L. (2002). Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition*, *82*(3), B101-B111. https://doi.org/10.1016/S0010-0277(01)00157-3

Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition*, *29*(2), 143-178. https://doi.org/10.1016/0010-0277(88)90035-2

Menn, K. H., Männel, C., & Meyer, L. (2023). Does Electrophysiological Maturation Shape Language Acquisition? *Perspectives on Psychological Science*, *18*(6), 1271-1281. https://doi.org/10.1177/17456916231151584

Moon, C., Cooper, R. P., & Fifer, W. P. (1993). Two-day-olds prefer their native language. *Infant Behavior and Development*, *16*(4), 495-500. https://doi.org/10.1016/0163-6383(93)80007-U

Moon, C., Lagercrantz, H., & Kuhl, P. K. (2013). Language experienced *in utero* affects vowel perception after birth: A two□country study. *Acta Paediatrica*, *102*(2), 156-160. https://doi.org/10.1111/apa.12098

Moore, J. K., & Linthicum, F. H. (2007). The human auditory system: A timeline of development. *International Journal of Audiology*, *46*(9), 460-478. https://doi.org/10.1080/14992020701383019

Moore, J. K., Perazzo, L. M., & Braun, A. (1995). Time course of axonal myelination in the human brainstem auditory pathway. *Hearing Research*, *87*(1-2), 21-31. https://doi.org/10.1016/0378-5955(95)00073-D

Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: Toward an understanding of the role of rhythm. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 756-766. https://doi.org/10.1037/0096-1523.24.3.756

Oller, D. K. (1992). Description of Infant Vocalizations and Young Child Speech: Theoretical and Practical Tools. *Seminars in Speech and Language*, *13*(03), 178-193. https://doi.org/10.1055/s-2008-1064196

Partanen, E., Kujala, T., Tervaniemi, M., & Huotilainen, M. (2013b). Prenatal Music Exposure Induces Long-Term Neural Effects. *PLoS ONE*, *8*(10), e78946. https://doi.org/10.1371/journal.pone.0078946

Peña, M., Pittaluga, E., & Mehler, J. (2010). Language acquisition in premature and full-term infants. *Proceedings of the National Academy of Sciences*, *107*(8), 3823-3828. https://doi.org/10.1073/pnas.0914326107

Peña, M., Werker, J. F., & Dehaene-Lambertz, G. (2012). Earlier Speech Exposure Does Not Accelerate Speech Acquisition. *Journal of Neuroscience*, *32*(33), 11159-11163. https://doi.org/10.1523/JNEUROSCI.6516-11.2012

Puertollano, M., Ribas-Prats, T., Gorina-Careta, N., Ijjou-Kadiri, S., Arenillas-Alcón, S., Mondéjar-Segovia, A., Dolores Gómez-Roig, M., & Escera, C. (2024). Longitudinal trajectories of the neural encoding mechanisms of speech-sound features during the first year of life. *Brain and Language*, *258*, 105474. https://doi.org/10.1016/j.bandl.2024.105474

Quast, A., Hesse, V., Hain, J., Wermke, P., & Wermke, K. (2016). Baby babbling at five months linked to sex hormone levels in early infancy. *Infant Behavior and Development*, *44*, 1-10. https://doi.org/10.1016/j.infbeh.2016.04.002

Querleu, D., Renard, X., Versyp, F., Paris-Delrue, L., & Crèpin, G. (1988). Fetal hearing. *European Journal of Obstetrics & Gynecology and Reproductive Biology*, *28*(3), 191-212. https://doi.org/10.1016/0028-2243(88)90030-5

Ribas-Prats, T., Almeida, L., Costa-Faidella, J., Plana, M., Corral, M. J., Gómez-Roig, M. D., & Escera, C. (2019). The frequency-following response (FFR) to speech stimuli: A normative dataset in healthy newborns. *Hearing Research*, *371*, 28-39. https://doi.org/10.1016/j.heares.2018.11.001

Ribas□Prats, T., Arenillas□Alcón, S., Lip□Sosa, D. L., Costa□Faidella, J., Mazarico, E., Gómez□Roig, M. D., & Escera, C. (2022). Deficient neural encoding of speech sounds in term neonates born after fetal growth restriction. *Developmental Science*, *25*(3), e13189. https://doi.org/10.1111/desc.13189

Ribas-Prats, T., Arenillas-Alcón, S., Pérez-Cruz, M., Costa-Faidella, J., Gómez-Roig, M. D., & Escera, C. (2023a). Speech-encoding deficits in neonates born large-for-gestational age as revealed with the envelope Frequency-Following

915 Response. *Ear & Hearing*, *44*(4), 829-841.
916 https://doi.org/10.1097/AUD.0000000000001330
917 Ribas-Prats, T., Cordero, G., Lip-Sosa, D. L., Arenillas-Alcón, S., Costa-Faidella, J.,
918 Gómez-Roig, M. D., & Escera, C. (2023b). Developmental trajectory of the
919 Frequency-Following Response during the first 6 months of life. *Journal of*
920 *Speech, Language, and Hearing Research*, *66*(12), 4785-4800.
921 https://doi.org/10.1044/2023_JSLHR-23-00104
922 Rivera□Gaxiola, M., Silva□Pereyra, J., & Kuhl, P. K. (2005). Brain potentials to native
923 and non□native speech contrasts in 7□ and 11□month□old American infants.
924 *Developmental Science*, *8*(2), 162-172. https://doi.org/10.1111/j.1467-
925 7687.2005.00403.x
926 Ruben, R. J. (1995). The ontogeny of human hearing. *International Journal of Pediatric*
927 *Otorhinolaryngology*, *32*, S199-S204. https://doi.org/10.1016/0165-
928 5876(94)01159-U
929 Schaadt, G., Hesse, V., & Friederici, A. D. (2015). Sex hormones in early infancy seem
930 to predict aspects of later language development. *Brain and Language*, *141*, 70-
931 76. https://doi.org/10.1016/j.bandl.2014.11.015
932 Schaadt, G., Werwach, A., Obrig, H., Friederici, A. D., & Männel, C. (2023).
933 Maturation of consonant perception, but not vowel perception, predicts lexical
934 skills at 12 months. *Child Development*, *94*(3), e166-e180.
935 https://doi.org/10.1111/cdev.13892
936 Schneider, U., Schleussner, E., Haueisen, J., Nowak, H., & Seewald, H. (2001). Signal
937 Analysis of Auditory Evoked Cortical Fields in Fetal Magnetoencephalography.
938 *Brain Topography*, *14*(1), 69-80. https://doi.org/10.1023/A:1012519923583

939 Skoe, E., Burakiewicz, E., Figueiredo, M., & Hardin, M. (2017). Basic neural
940 processing of sound in adults is influenced by bilingual experience.
941 *Neuroscience, 349*, 278-290. https://doi.org/10.1016/j.neuroscience.2017.02.049
942 Skoe, E., & Kraus, N. (2010). Auditory Brain Stem Response to complex sounds: A
943 tutorial. *Ear and Hearing, 31*(3), 302.
944 https://doi.org/10.1097/AUD.0b013e3181cdb272
945 Sung, J., Fausto-Sterling, A., Garcia Coll, C., & Seifer, R. (2013). The dynamics of age
946 and sex in the development of mother–infant vocal communication between 3
947 and 11 months. *Infancy*, *18*(6), 1135-1158. https://doi.org/10.1111/infa.12019
948 The Jamovi Project. (2024). *Jamovi (Version 2.5) [Computer Software]* [Software].
949 https://www.jamovi.org
950 The MathWorks Inc. (2019). *MATLAB Version 9.7 (R2019b)* [Software].
951 https://www.mathworks.com
952 Tsao, F.-M., Liu, H.-M., & Kuhl, P. K. (2006). Perception of native and non-native
953 affricate-fricative contrasts: Cross-language tests on adults and infants. *The*
954 *Journal of the Acoustical Society of America*, *120*(4), 2285-2294.
955 https://doi.org/10.1121/1.2338290
956 Van Dyke, K. B., Lieberman, R., Presacco, A., & Anderson, S. (2017). Development of
957 phase locking and frequency representation in the infant Frequency-Following
958 Response. *Journal of Speech, Language, and Hearing Research, 60*(9), 2740-
959 2751. https://doi.org/10.1044/2017_JSLHR-H-16-0263
960 Voegtline, K. M., Costigan, K. A., Pater, H. A., & DiPietro, J. A. (2013). Near-term
961 fetal response to maternal spoken voice. *Infant Behavior and Development*,
962 *36*(4), 526-533. https://doi.org/10.1016/j.infbeh.2013.05.002

963 Werker, J. F., Byers-Heinlein, K., & Fennell, C. T. (2009). Bilingual beginnings to
964 learning words. *Philosophical Transactions of the Royal Society B: Biological*
965 *Sciences*, *364*(1536), 3649-3663. https://doi.org/10.1098/rstb.2009.0105
966 Werker, J. F., Gilbert, J. H. V., Humphrey, K., & Tees, R. C. (1981). Developmental
967 Aspects of Cross-Language Speech Perception. *Child Development*, *52*(1), 349.
968 https://doi.org/10.2307/1129249
969 Werker, J. F., & Hensch, T. K. (2015). Critical periods in speech perception: New
970 directions. *Annual Review of Psychology*, *66*(1), 173-196.
971 https://doi.org/10.1146/annurev-psych-010814-015104
972 Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for
973 perceptual reorganization during the first year of life. *Infant Behavior and*
974 *Development*, *7*(1), 49-63. https://doi.org/10.1016/S0163-6383(84)80022-3
975 Wermke, K., Hain, J., Oehler, K., Wermke, P., & Hesse, V. (2014). Sex hormone
976 influence on human infants' sound characteristics: Melody in spontaneous
977 crying. *Biology Letters*, *10*(5), 20140095. https://doi.org/10.1098/rsbl.2014.0095
978 Werwach, A., Männel, C., Obrig, H., Friederici, A. D., & Schaadt, G. (2022).
979 Longitudinal trajectories of electrophysiological mismatch responses in infant
980 speech discrimination differ across speech features. *Developmental Cognitive*
981 *Neuroscience*, *56*, 101127. https://doi.org/10.1016/j.dcn.2022.101127
982 Whitehouse, A. J. O., Mattes, E., Maybery, M. T., Sawyer, M. G., Jacoby, P., Keelan, J.
983 A., & Hickey, M. (2012). Sex□specific associations between umbilical cord
984 blood testosterone levels and language delay in early childhood. *Journal of*
985 *Child Psychology and Psychiatry*, *53*(7), 726-734.
986 https://doi.org/10.1111/j.1469-7610.2011.02523.x

White-Schwoch, T., Davies, E. C., Thompson, E. C., Woodruff Carr, K., Nicol, T., Bradlow, A. R., & Kraus, N. (2015). Auditory-neurophysiological responses to speech during early childhood: Effects of background noise. *Hearing Research*, *328*, 34-47. https://doi.org/10.1016/j.heares.2015.06.009

Xu, G., Broadbelt, K. G., Haynes, R. L., Folkerth, R. D., Borenstein, N. S., Belliveau, R. A., Trachtenberg, F. L., Volpe, J. J., & Kinney, H. C. (2011). Late Development of the GABAergic System in the Human Cerebral Cortex and White Matter. *Journal of Neuropathology & Experimental Neurology*, *70*(10), 841-858. https://doi.org/10.1097/NEN.0b013e31822f471c

Zhao, T. C., Llanos, F., Chandrasekaran, B., & Kuhl, P. K. (2022). Language experience during the sensitive period narrows infants' sensory encoding of lexical tones—Music intervention reverses it. *Frontiers in Human Neuroscience*, *16*, 941853. https://doi.org/10.3389/fnhum.2022.941853