Does Electrophysiological Maturation Shape Language Acquisition?

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Abstract

Infants master temporal patterns of their native language at a developmental trajectory from slow to fast: Shortly after birth, they recognize the slow acoustic modulations specific to their native language before tuning into faster language-specific patterns between 6 and 12 months of age. We propose here that this trajectory is constrained by neuronal maturation—in particular, the gradual emergence of high-frequency neural oscillations in the infant electroencephalogram. Infants' initial focus on slow prosodic modulations is consistent with the prenatal availability of slow electrophysiological activity (i.e., theta- and delta-band oscillations). Our proposal is consistent with the temporal patterns of infant-directed speech, which initially amplifies slow modulations, approaching the faster modulation range of adult-directed speech only as infants' language has advanced sufficiently. Moreover, our proposal agrees with evidence from premature infants showing maturational age is a stronger predictor of language development than ex utero exposure to speech, indicating that premature infants cannot exploit their earlier availability of speech because of electrophysiological constraints. In sum, we provide a new perspective on language acquisition emphasizing neuronal development as a critical driving force of infants' language development.

Keywords

oscillations, infant-directed speech, neural development, temporal speech patterns

Before birth and in the first months afterward, the electrophysiological spectrum of the brain is dominated by slow activity (Fig. 1a). Delta-band activity emerges from around 24 weeks gestational age as discontinuous activity at a frequency of approximately 0.5 Hz (Vecchierini et al., 2007). The delta activity arises from the early maturation of thalamocortical connections (Arichi et al., 2017; Kidokoro, 2021). From around 31 weeks gestational age, delta activity can be exogenously evoked by sound (Chipaux et al., 2013). Somewhat earlier at around 28 weeks gestational age, slow-wave theta-band activity (4–8 Hz; TTA-SW) adds to delta. TTA-SW originates from areas close to the typical auditory and language-relevant areas (Moghimi et al., 2020). TTA-SW is insensitive to sensory input and has been argued to reflect the endogenous preparation of these areas (Routier et al., 2017). As we discuss in detail below, exogenous neural

oscillations faster than the delta bands are virtually absent from the fetal brain and emerge only after birth (Anderson & Perone, 2018; Moghimi et al., 2020; Routier et al., 2017; Vanhatalo et al., 2002).

In contrast, adult speech processing is thought to use a more extended range of exogenous oscillatory activity. Exogenous oscillations in the delta and theta bands, but also faster oscillations in the gamma band (> 20 Hz), are thought to serve the temporal segmentation of speech. This may be achieved via phase alignment of the gamma, theta, and delta bands to acoustic modulations in speech (Assaneo & Poeppel, 2018;

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a

EEG Development: Ontogenic Growth in High-Frequency Activity

b

Speech: Temporal and Spectral Information

The little polar bear lived in ice and snow

Intonation (< 4 Hz)
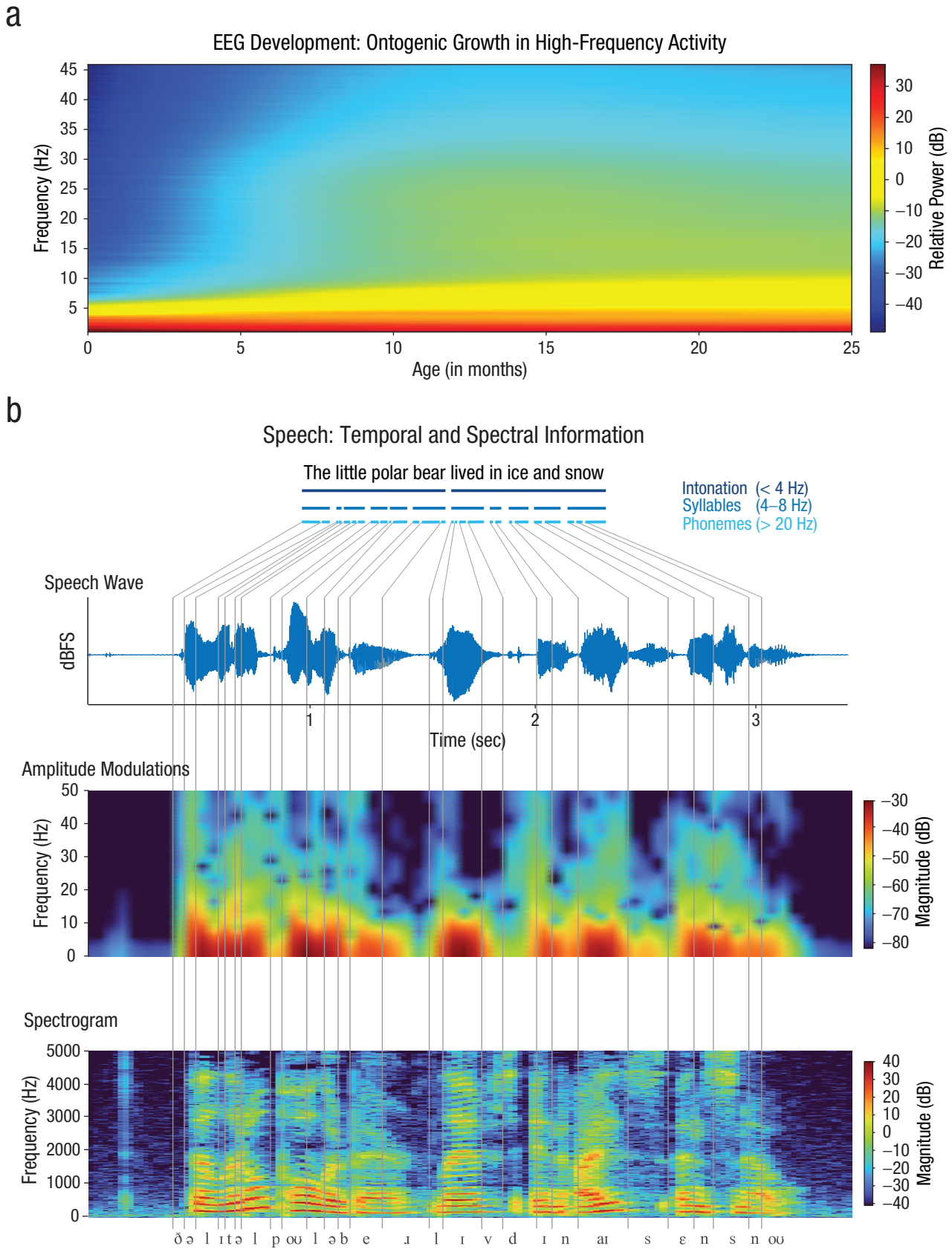Syllables   (4–8 Hz)
Phonemes (> 20 Hz)

Fig. 1. Overview of electrophysiological development across the first 2 years and the temporal and spectral information in speech. The electrophysiological activity during story listening is initially constrained to low frequencies below 10 Hz, but it speeds up across development (modelled from Menn, Männel, & Meyer, 2022) (a). Faster frequencies emerge at around 6 months. Temporal information in speech is assumed to match acoustic grain sizes of phonemes, syllables, and intonation phrases (b). The segmentation and identification of linguistic content require the modulation spectrum, obtained from the envelope, and the spectrogram, which shows spectrotemporal modulations and formant structure.
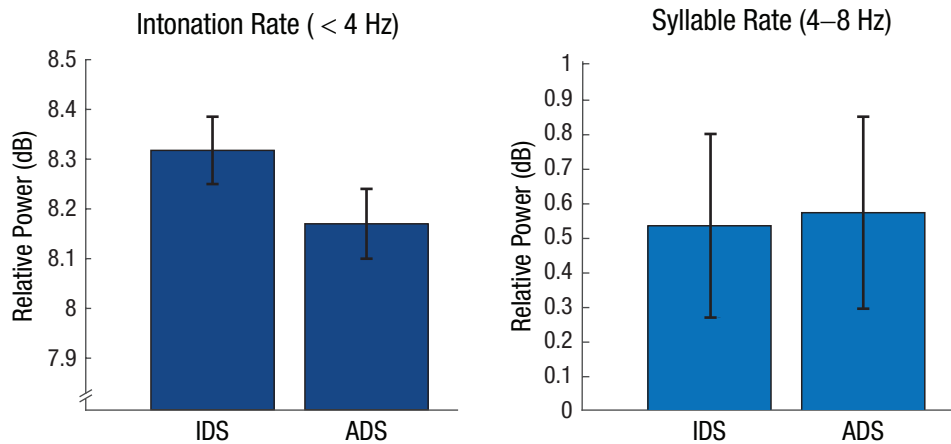
Fig. 2. Differences in amplitude modulations between infant-directed speech (IDS) and adult-directed speech (ADS) in the intonation and syllable rate. Parents enhance amplitude modulations in the intonation rate when interacting with infants compared with interactions with adults, in line with earlier findings (Leong et al., 2017; Menn, Michel, et al., 2022). Data were taken from the Newman-Ratner Corpus in CHILDES (Newman et al., 2016). IDS data are from eight representative interactions between mothers and their 7-month-old infant, and ADS data are from interactions between the same mothers and an experimenter. Error bars indicate standard errors.

Giraud & Poeppel, 2012; Meyer, 2018; Poeppel & Assaneo, 2020). The frequencies of these bands are thought to match to the acoustic grain sizes of phonemes, syllables, and intonation phrases, respectively (Fig. 1b; Leong & Goswami, 2015; Poeppel & Assaneo, 2020). There is clear evidence that phase alignment with the corresponding acoustic modulations facilitates speech processing, as its magnitude predicts intelligibility (Peelle et al., 2013).

The Primacy of Slowness in Early Linguistic Abilities

Newborns display selective acquaintance with slow temporal patterns characteristic of the speech prosody of their native language (Byers-Heinlein et al., 2010; Gasparini et al., 2021; Nazzi et al., 2000; Ramus, 2002). But this does not mean that newborns can yet tell their native language from any other language. Instead, they show a listening preference for speech that shares the prosodic rhythm of their mother's language—that is, including rhythmically similar nonnative languages (Byers-Heinlein et al., 2010; Mehler et al., 1988; Moon et al., 1993; Nazzi & Ramus, 2003). Given newborns' expertise in slow temporal patterns of speech prosody, they must acquire these patterns in utero. Indeed, hearing abilities emerge already toward the end of the second trimester of gestation (i.e., at approximately 25–29 weeks gestational age; Birnholz & Benacerraf, 1983), and the fetal brain processes speech and nonspeech sounds at least during the last trimester (Draganova et al., 2018; Hartkopf et al., 2016; Hykin et al., 1999;

Muenssinger et al., 2013; Wakai et al., 1996). At this age, the auditory system is fully developed structurally and connected to the thalamus (Ghio et al., 2021; Khan et al., 2019; Takahashi et al., 2012).

Infant-Directed Speech: Just Slow Enough for the Infant Brain?

Infant-directed speech (IDS) is marked by a slow articulation rate and lengthened, hyperarticulated vowels (Casillas et al., 2020; Cristia, 2013, 2022; Fernald et al., 1989; Soderstrom, 2007; Spinelli et al., 2017). Moreover, slow amplitude modulations (< 4 Hz) are enhanced in IDS even independently of speech rate (Fig. 2; Leong et al., 2017). These adaptations have a number of behavioral benefits, such as increasing infants' attention toward IDS compared with adult-directed speech (ManyBabies Consortium, 2020; Werker & McLeod, 1989).

Slowness also aids language development (Golinkoff et al., 2015)—presumably by amplifying those temporal patterns that infant electrophysiology is equipped to process well. A slower initial speaking rate by caregivers seems to be beneficial for language acquisition and predicts infants' later vocabulary (Raneri et al., 2020). Most critically, infants are sensitive to caregivers' enhancement of prosodic information and show a stronger neural phase alignment to IDS compared with adult-directed speech specifically for the prosodic rate (Menn, Michel, et al., 2022). In other words, caregivers' enhancement of slow temporal patterns in IDS would facilitate electrophysiological processing by the delta-dominant infant

brain. The emphasis on prosodic information could further highlight the parts of the acoustic speech that signals the onset of linguistic units, and it has been shown that the tracking of prosody in infancy predicts the acquisition of vocabulary (Menn, Ward, et al., 2022). This link between prosodic and linguistic processing in infants is supported by behavioral evidence of prosodic bootstrapping—the finding that infants use prosodic information to infer linguistic units (Gervain & Werker, 2013; Gleitman & Wanner, 1982; Soderstrom et al., 2003).

Early Low-Pass Filtering of Speech: The Womb Versus the Brain

It is traditionally thought that fetuses cannot acquire temporal patterns faster than prosodic modulations mainly because the former cannot be heard in the womb (for reviews, see Gervain, 2018; Nallet & Gervain, 2021). Indeed, the maternal tissue that surrounds the fetus acts as a low-pass filter that limits the conduction of high-frequency sound (Fig. 3a). Recordings from nonhuman mammals (e.g., sheep) and results from simulation studies suggest that slow temporal patterns of speech prosody are well preserved, but frequencies above 400 to 600 Hz are strongly attenuated in the womb (Gerhardt & Abrams, 1996; Griffiths et al., 1994; Lecanuet & Granier-Deferre, 1993; Querleu et al., 1988). This suggests that the low-pass filtering of the maternal tissue strongly affects the spectral information of speech but has a limited effect on amplitude modulations, which cue onsets of new segments in continuous speech (Fig. 3b and 3c). If the acoustic filter of the womb is the only constraint on learning, fetuses should be able to exploit their prenatal exposure to segmentation cues. But this is not the case: Although newborns show phonemic perceptual learning for individually presented vowels (Wu et al., 2022), they do not yet show the ability to segment fast speech sounds from continuous speech (Bijeljac-Babic et al., 1993), indicating a maturational rather than environmental constraint on the processing of fast modulations in speech, as this information was already available in utero.

Additional evidence for maturational constraints on fast temporal information processing comes from premature infants. Given that prematurely born infants are exposed to unfiltered speech earlier than full-term infants, they should have a head start in the acquisition of faster temporal patterns, such as those required to segment phonemes. But this is not the case: Infants who are born prematurely do not tune into fast temporal patterns of their native language earlier than infants born full term—that is, they do not build native phoneme categories any earlier (Peña et al., 2012). This suggests that maturational age rather than exposure limits the time scale of processing to slow temporal patterns. This is compatible with our proposal that early language development is constrained by electrophysiological maturation: Slow oscillatory frequencies are present already in the fetal brain, whereas faster frequencies emerge only after birth, that is, after the maturation of the underlying neural tissue.

Fast Electrophysiological Activity Emerges Late

Even after birth, slow electrophysiological activity continues to dominate infants' electrophysiological power spectrum. Until shortly after birth, electrophysiological activity in the gamma range cannot be detected (Le Van Quyen et al., 2006). Within the first 6 months after birth, the spectrum flattens out, and the initial strong prevalence of slow electrophysiological activity decreases as high-frequency activity increases (Fig. 1a; Schaworonkow & Voytek, 2021). This is due to the gradual emergence of fast electrophysiological activity (i.e., gamma-range activity; Le Van Quyen et al., 2006). The reason why the gamma band emerges late is the ontogenetic maturation of the underlying brain tissue. In particular, the migration of GABAergic neurons continues until 6 months postnatally (Xu et al., 2011). Gamma-band activity relies on the rapid interaction between excitatory and inhibitory interneurons (Cardin et al., 2009; Fries et al., 2007). In adults, these inhibitory interneurons are mostly GABAergic (Kravitz et al., 1963; Purpura et al., 1957). Prenatally, however, differences in fetal neurochemistry cause GABA to have an excitatory effect (Dammerman et al., 2000; Gao & Van Den Pol, 2001; Owens et al., 1996, 1999). For inhibition, the fetal brain mostly relies on giant depolarizing potentials, which are too slow to allow for the emergence of faster oscillations in the gamma-range rhythms (Ben-Ari, 2002; Khazipov et al., 2004; Le Van Quyen et al., 2006).

No Gamma, No Native Phoneme Inventory

The gradual emergence of gamma-band oscillations in infancy could explain the developmental trajectory of phonological acquisition. As noted above, in adults, neural activity in the lower gamma band has been linked to the segmentation of phonemes from speech. This is thought to be achieved by phase alignment with phoneme-rate amplitude modulations (Fig. 4a; Di Liberto et al., 2015; Goswami, 2019; Gross et al., 2013).

Electrophysiological activity that could phase-align to phoneme-rate amplitude modulations emerges until the age of 6 months (Le Van Quyen et al., 2006; Xu et al., 2011). During this age precisely, infants start building an inventory of native phonemes (i.e., speech
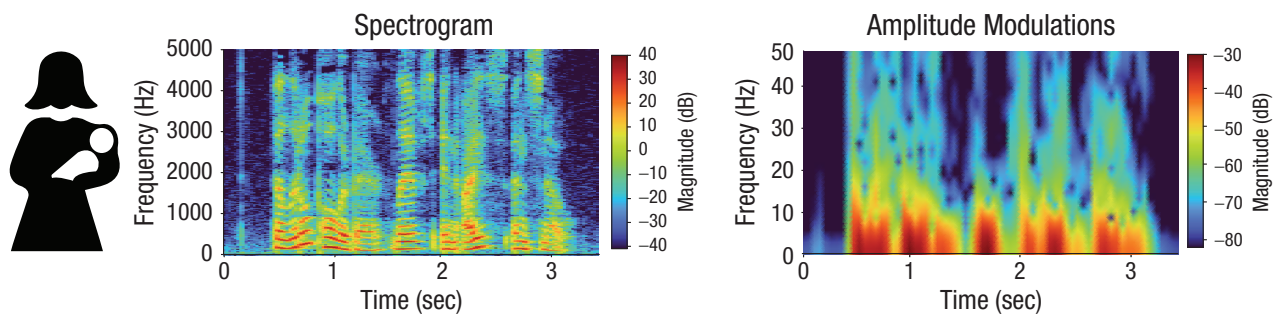
a

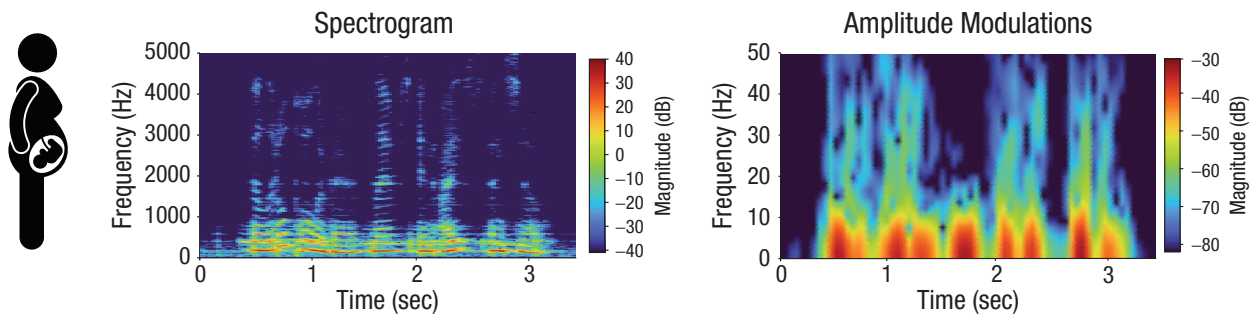### The Womb as a Low-Pass Filter of Speech
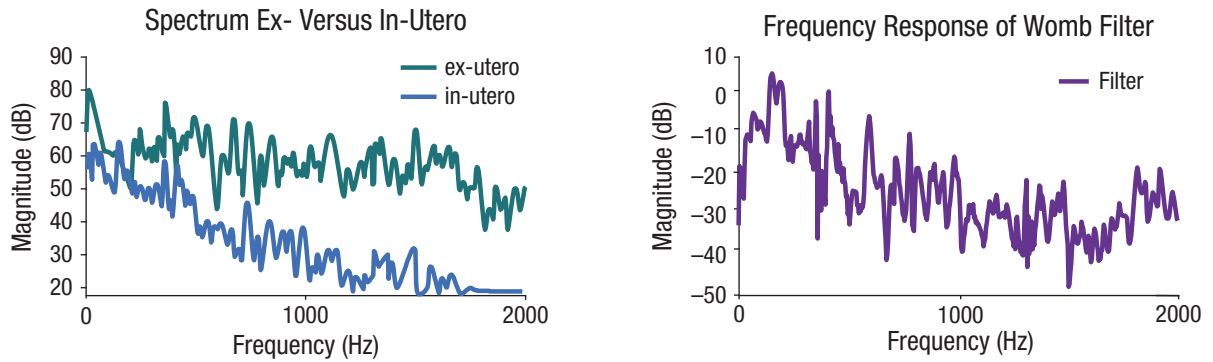
Fig. 3. Availability of acoustic information from speech in the womb. The availability of temporal speech information inside the womb was estimated by reconstructing the womb filter from the in utero and ex utero spectrum described and depicted in Querleu et al. (1988; a). The low-pass filtering of the maternal tissue strongly affects the spectral information in speech but has less effect on amplitude modulations (b, c).

sounds; Kuhl, 2004; Tsuji & Cristia, 2014). This is indicated by the emergence of the so-called perceptual magnet effect: Infants misperceive nonnative phonemes as instances of native phonemes—that is, their native categorical knowledge exerts a top-down influence over their auditory perception. Before this age, infants can dissociate nonnative and native phonemes with equal acuity (Werker, 1995).

Before acquiring their native phonological inventory, infants must first be able to segment the acoustic segments corresponding to individual phonemes in speech. Critically, this requires a higher temporal resolution than available without the electrophysiological gamma band: Studies on adults suggest that two phonemes can be perceived only as separate acoustic segments if they are separated by at least 20 ms, such that they can

trigger phase-locking of two independent gamma cycles (Giraud, 2020; Joliot et al., 1994). Strikingly, 4-day-old newborns do not discriminate bisyllabic utterances that differ only in the number of phonemes within the syllable (Bijeljac-Babic et al., 1993). Given that phoneme-rate amplitude modulations are available to the fetus in utero, this null finding indicates maturational constraints on phoneme segmentation. Even at 7.5 months of age, infants can dissociate both pure tones and phonemes only when these are at least approximately 75 ms apart (Benasich & Tallal, 2002; Partanen et al., 2013). In the visual domain, this processing slowness has even more drastic effects: 5-month-olds require an interval of more than a second to perceive two stimuli as independent (Hochmann & Kouider, 2022; Tsurumi et al., 2021). These modality-dependent effects may be an additional challenge for the acquisition of native phonemes, for which infants also rely on visual cues (e.g., mouth movements; Altvater-Mackensen et al., 2016; Burnham & Dodd, 2004; Ter Schure et al., 2016). Until now, the developmental trajectory of phoneme-rate amplitude tracking during infancy has not been assessed, but we hypothesize that neural tracking of fast temporal information develops only during infancy—and that it arises only after infants' temporal integration windows have decreased sufficiently to perceive individual phonemes separately.

Gamma-Band Maturation: A Critical Period for Phoneme Acquisition?

Clinical work suggests that phoneme-level acquisition and processing depends on the emergence of gamma-band activity around the age of 6 months. Six-month-old infants at familial risk for language impairments display decreased gamma-band activity during rapid auditory processing (Cantiani et al., 2019). Moreover, developmental language disorder has been related to reduced gamma-rate activity both during rest (Benasich et al., 2008) and during rapid auditory processing (Heim et al., 2013). Developmental language disorder is marked by phoneme-level difficulties that are linked to a generalized deficit in the processing of fast acoustic transitions (Corriveau et al., 2007; Richards & Goswami, 2015; Tallal & Piercy, 1973). In line with this, such difficulties are most pronounced at high speech rates, for which processing relies on even higher frequencies (Guiraud et al., 2018).

From Low to High Gamma—From Segmentation to Representation?

So far, we have considered the role of the gamma band in phoneme-rate speech segmentation. Importantly, this role can be served only by the lower gamma band (i.e., > 25 Hz), which covers frequencies that can phase-lock to phoneme-rate amplitude modulations in speech (Leong & Goswami, 2015; O'Shaughnessy, 1995). In contrast to segmentation, the establishment of a native phoneme inventory cannot rely on the lower gamma band alone.

In adults, activity in the higher gamma band (i.e., > 70 Hz) is sensitive to phonological features (Fig. 4b; Nourski et al., 2015; Steinschneider et al., 2011). Feature processing has been related to neuronal spiking in the auditory association cortex that is sensitive to individual phonological features (Mesgarani et al., 2014).

The different proposed functional roles of the lower and higher gamma bands would entail that infants first learn to segment phonemes (= lower gamma) and afterward acquire their categorical properties (= higher gamma, spiking activity). There is indirect evidence for this idea: First, the developmental shift from slow to fast electrophysiological activity does not stop at the lower gamma band but continues until the higher gamma band (Cellier et al., 2021; Pivik et al., 2019; Schaworonkow & Voytek, 2021). Second, Ortiz-Mantilla et al. (2013) tested 6-month-old infants on their perception of native and nonnative phonemic contrasts. At this age, activity in the lower gamma band (i.e., 30–34 Hz) increased for the native compared with the nonnative contrast. At 12 months of age, this effect shifted to the higher gamma band (i.e., 70–77 Hz; Ortiz-Mantilla et al., 2016). Third, there is evidence from investigations of infants' ability to discriminate their native language from languages with a similar rhythm. We noted above that the ability to discriminate between rhythmically similar languages (e.g., Catalan and Spanish) emerges only between 4 and 5 months of age (Bosch & Sebastián-Gallés, 1997). Because prosodic information is insufficient for the discrimination of such rhythmically similar languages, their discrimination requires sensitivity to faster, phoneme-rate modulations. Infants' progression from a general perception of global rhythmic features to more fine-grained perception of native sound organization is accompanied by neural activity in the gamma range. Activity in the lower gamma band is seen when infants are listening to languages rhythmically similar to their native language by 3 months of age (Nacar Garcia et al., 2018; Peña et al., 2010). However, activity in the higher gamma band (55–75 Hz) increases for the native language from 6 months of age (Peña et al., 2010).

IDS Accelerates: In Pursuit of Electrophysiological Maturation?

Although IDS is initially slow, caregivers accelerate their speech patterns across development; speech rate becomes comparable to adult-directed speech at around
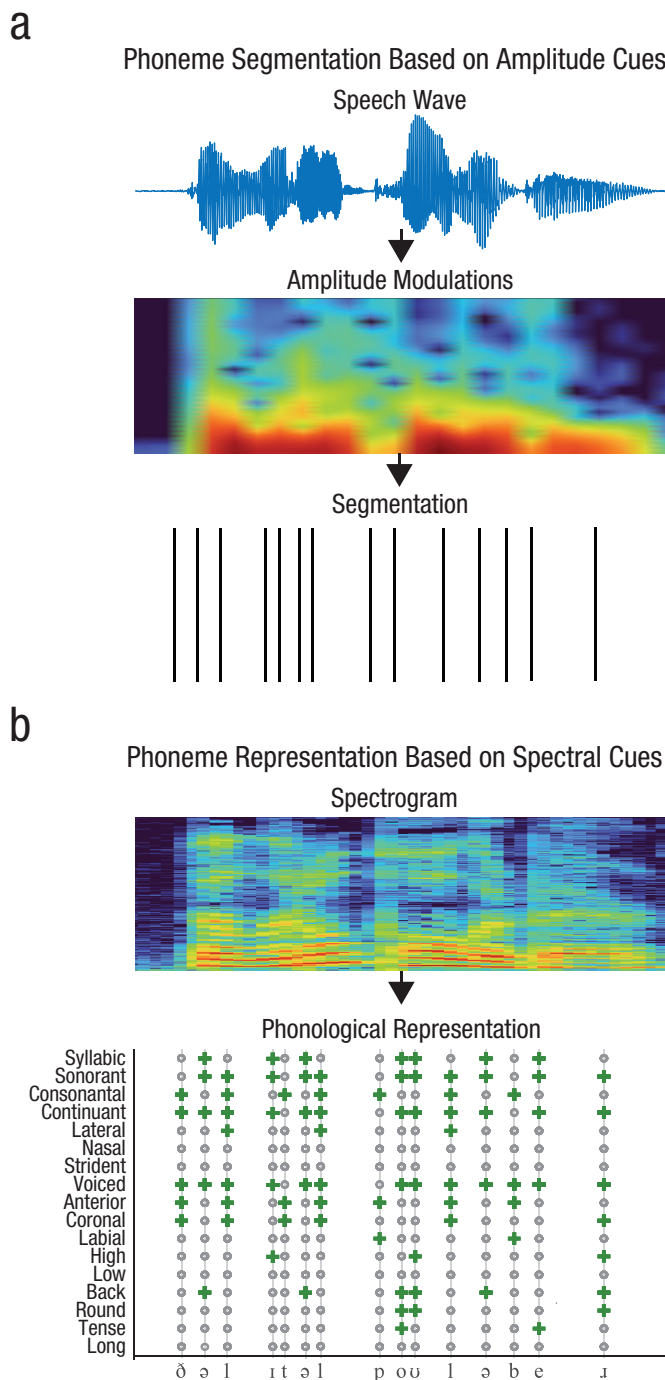
a

Phoneme Segmentation Based on Amplitude Cues

Speech Wave

Amplitude Modulations

Segmentation

b

Phoneme Representation Based on Spectral Cues

Spectrogram

Phonological Representation

Fig. 4. Phoneme segmentation does not equal phoneme representation. Phoneme segmentation from continuous speech is based on amplitude modulations > 20 Hz that cue phoneme onsets (a). On a neural level, segmentation is achieved by lower gamma activity tracking phoneme-rate amplitude modulations. Phonological representations are based on spectrogram information in speech (b). On a neural level, higher gamma activity is required for the representation of phonological features.

2 years of infant age (Kondaurova et al., 2013; Lee et al., 2014; Narayan & McDermott, 2016; Raneri et al., 2020). In addition to adaptations of speech rate, caregivers have been found to prolong vowels in IDS (Englund & Behne, 2006; Hilton et al., 2022; Kondaurova & Bergeson, 2011; Lovcevic et al., 2020). The prolongation of vowels may ease phoneme-rate segmentation for the slow infant brain; moreover, it may help to make phonological contrasts more salient in time by slowing down the rate of phonological feature changes. Caregivers were also shown to decrease vowel duration differences between IDS and adult-directed speech as infants get older (Englund & Behne, 2006; Hartman et al., 2017; Vosoughi & Roy, 2012), possibly aligning the phoneme rate of their speech to infants' increasing electrophysiological processing speed.

Conclusion

We presented a new perspective on the relationship between electrophysiological maturation and language acquisition. Specifically, the prenatal prevalence of slow electrophysiological activity allows for the early development of native-specific speech processing of prosodic information, which is available to the fetus in utero. Faster electrophysiological activity in the gamma range, which is required for the segmentation and representation of native phonological information, emerges only postnatally and continues to develop across the first year after birth, therefore constraining the onset of the acquisition of acoustic-phonological knowledge to the second half of the infants' first year. Parental speech adaptations fit the temporal granularity of infants' electrophysiological tool kit. This provides a novel perspective for the neuroscientific investigation of language acquisition. Researchers should consider infants' learning in relationship to their electrophysiological processing abilities as well as the speech they receive from their caregivers. Novel studies on infant's electrophysiological speech processing should specifically focus on electrophysiological processing of frequency modulations, which are highly relevant for language development, as well as more directly on the role of gamma activity for infants' early phonological acquisition.

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References

Altvater-Mackensen, N., Mani, N., & Grossmann, T. (2016). Audiovisual speech perception in infancy: The influence of vowel identity and infants' productive abilities on sensitivity to (mis) matches between auditory and visual speech cues. *Developmental Psychology*, *52*(2), 191–204.

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

Arichi, T., Whitehead, K., Barone, G., Pressler, R., Padormo, F., Edwards, A. D., & Fabrizi, L. (2017). Localization of spontaneous bursting neuronal activity in the preterm human brain with simultaneous EEG-fMRI. *eLife*, *6*, Article e27814. https://doi.org/10.7554/eLife.27814

Assaneo, M. F., & Poeppel, D. (2018). The coupling between auditory and motor cortices is rate-restricted: Evidence for an intrinsic speech-motor rhythm. *Science Advances*, *4*(2), Article eaao3842. https://doi.org/10.1126/sciadv.aao3842

Ben-Ari, Y. (2002). Excitatory actions of gaba during development: The nature of the nurture. *Nature Reviews Neuroscience*, *3*(9), 728–739.

Benasich, A. A., Gou, Z., Choudhury, N., & Harris, K. D. (2008). Early cognitive and language skills are linked to resting frontal gamma power across the first 3 years. *Behavioural Brain Research*, *195*(2), 215–222.

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioural Brain Research*, *136*(1), 31–49.

Bijeljac-Babic, R., Bertoncini, J., & Mehler, J. (1993). How do 4-day-old infants categorize multisyllabic utterances? *Developmental Psychology*, *29*(4), 711–721.

Birnholz, J. C., & Benacerraf, B. R. (1983). The development of human fetal hearing. *Science*, *222*(4623), 516–518.

Bosch, L., & Sebastián-Gallés, N. (1997). Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. *Cognition*, *65*(1), 33–69.

Burnham, D., & Dodd, B. (2004). Auditory–visual speech integration by prelinguistic infants: Perception of an emergent consonant in the McGurk effect. *Developmental Psychobiology*, *45*(4), 204–220.

Byers-Heinlein, K., Burns, T. C., & Werker, J. F. (2010). The roots of bilingualism in newborns. *Psychological Science*, *21*(3), 343–348.

Cantiani, C., Ortiz-Mantilla, S., Riva, V., Piazza, C., Bettoni, R., Musacchia, G., Molteni, M., Marino, C., & Benasich, A. A. (2019). Reduced left-lateralized pattern of event-related EEG oscillations in infants at familial risk for language and learning impairment. *NeuroImage: Clinical*, *22*, Article 101778. https://doi.org/10.1016/j.nicl.2019.101778

Cardin, J. A., Carlén, M., Meletis, K., Knoblich, U., Zhang, F., Deisseroth, K., Tsai, L.-H., & Moore, C. I. (2009). Driving fast-spiking cells induces gamma rhythm and controls sensory responses. *Nature*, *459*(7247), 663–667.

Casillas, M., Brown, P., & Levinson, S. C. (2020). Early language experience in a tseltal mayan village. *Child Development*, *91*(5), 1819–1835.

Cellier, D., Riddle, J., Petersen, I., & Hwang, K. (2021). The development of theta and alpha neural oscillations from ages 3 to 24 years. *Developmental Cognitive Neuroscience*, *50*, Article 100969. https://doi.org/10.1016/j.dcn.2021.100969

Chipaux, M., Colonnese, M. T., Mauguen, A., Fellous, L., Mokhtari, M., Lezcano, O., Milh, M., Dulac, O., Chiron, C., Khazipov, R., & Kaminska, A. (2013). Auditory stimuli mimicking ambient sounds drive temporal "delta-brushes" in premature infants. *PLOS ONE*, *8*(11), Article e79028. https://doi.org/10.1371/journal.pone.0079028

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*(3), 647–666. https://doi.org/10.1044/1092-4388(2007/046)

Cristia, A. (2013). Input to language: The phonetics and perception of infant-directed speech. *Linguistics and Language Compass*, *7*(3), 157–170. https://doi.org/10.1111/lnc3.12015

Cristia, A. (2022). A systematic review suggests marked differences in the prevalence of infant-directed vocalization across groups of populations. *Developmental Science*, *26*(1), Article e13265. https://doi.org/10.1111/desc.13265

Dammerman, R., Flint, A., Noctor, S., & Kriegstein, A. (2000). An excitatory GABAergic plexus in developing neocortical layer 1. *Journal of Neurophysiology*, *84*(1), 428–434.

Di Liberto, G. M., O'Sullivan, J. A., & Lalor, E. C. (2015). Low-frequency cortical entrainment to speech reflects phoneme-level processing. *Current Biology*, *25*(19), 2457–2465.

Draganova, R., Schollbach, A., Schleger, F., Braendle, J., Brucker, S., Abele, H., Kagan, K., Wallwiener, D., Fritsche, A., Eswaran, H., & Preissl, H. (2018). Fetal auditory evoked responses to onset of amplitude modulated sounds. A fetal magnetoencephalography (fMEG) study. *Hearing Research*, *363*, 70–77.

Englund, K., & Behne, D. (2006). Changes in infant directed speech in the first six months. *Infant and Child Development*, *15*(2), 139–160.

Fernald, A., Taeschner, T., Dunn, J., Papousek, M., de Boysson-Bardies, B., & Fukui, I. (1989). A cross-language study of prosodic modifications in mothers' and fathers' speech to preverbal infants. *Journal of Child Language*, *16*(3), 477–501. https://doi.org/10.1017/S0305000900010679

Fries, P., Nikolić, D., & Singer, W. (2007). The gamma cycle. *Trends in Neurosciences*, *30*(7), 309–316.

Gao, X.-B., & Van Den Pol, A. N. (2001). Gaba, not glutamate, a primary transmitter driving action potentials in developing hypothalamic neurons. *Journal of Neurophysiology*, *85*(1), 425–434.

Gasparini, L., Langus, A., Tsuji, S., & Boll-Avetisyan, N. (2021). Quantifying the role of rhythm in infants' language discrimination abilities: A meta-analysis. *Cognition*, *213*, Article 104757. https://doi.org/10.1016/j.cognition.2021.104757

Gerhardt, K. J., & Abrams, R. M. (1996). Fetal hearing: Characterization of the stimulus and response. *Seminars in Perinatology*, *20*(1), 11–20.

Gervain, J. (2018). Gateway to language: The perception of prosody at birth. In H. Bartos, M. den Dikken, Z. Bánréti, & T. Váradi (Eds.), *Boundaries crossed, at the interfaces*

of morphosyntax, phonology, pragmatics and semantics (pp. 373–384). Springer.

Gervain, J., & Werker, J. F. (2013). Prosody cues word order in 7-month-old bilingual infants. *Nature Communications*, *4*(1), 1–6.

Ghio, M., Cara, C., & Tettamanti, M. (2021). The prenatal brain readiness for speech processing: A review on foetal development of auditory and primordial language networks. Neuroscience & Biobehavioral Reviews, *128*, 709–719.

Giraud, A.-L. (2020). Oscillations for all? A commentary on Meyer, Sun & Martin (2020). *Language, Cognition and Neuroscience*, *35*(9), 1106–1113. https://doi.org/10.1080/23273798.2020.1764990

Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging computational principles and operations. *Nature Neuroscience*, *15*(4), 511–517.

Gleitman, L. R., & Wanner, E. (1982). *Language acquisition: The state of the art*. Cambridge University Press.

Golinkoff, R. M., Can, D. D., Soderstrom, M., & Hirsh-Pasek, K. (2015). (Baby) talk to me: The social context of infant-directed speech and its effects on early language acquisition. *Current Directions in Psychological Science*, *24*(5), 339–344.

Goswami, U. (2019). Speech rhythm and language acquisition: An amplitude modulation phase hierarchy perspective. *Annals of the New York Academy of Sciences*, *1453*(1), 67–78.

Griffiths, S. K., Brown, W., Jr, Gerhardt, K. J., Abrams, R. M., & Morris, R. J. (1994). The perception of speech sounds recorded within the uterus of a pregnant sheep. *The Journal of the Acoustical Society of America*, *96*(4), 2055–2063.

Gross, J., Hoogenboom, N., Thut, G., Schyns, P., Panzeri, S., Belin, P., & Garrod, S. (2013). Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLOS Biology*, *11*(12), Article e1001752. https://doi.org/10.1371/journal.pbio.1001752

Guiraud, H., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Caillot-Bascoul, A., GonzalezMonge, S., & Boulenger, V. (2018). Don't speak too fast! Processing of fast rate speech in children with specific language impairment. *PLOS ONE*, *13*(1), Article e0191808. https://doi.org/10.1371/journal.pone.0191808

Hartkopf, J., Schleger, F., Weiss, M., Hertrich, I., Kiefer-Schmidt, I., Preissl, H., & Muenssinger, J. (2016). Neuromagnetic signatures of syllable processing in fetuses and infants provide no evidence for habituation. *Early Human Development*, *100*, 61–66.

Hartman, K. M., Ratner, N. B., & Newman, R. S. (2017). Infant-directed speech (IDS) vowel clarity and child language outcomes. *Journal of Child Language*, *44*(5), 1140–1162.

Heim, S., Keil, A., Choudhury, N., Friedman, J. T., & Benasich, A. A. (2013). Early gamma oscillations during rapid auditory processing in children with a language-learning impairment: Changes in neural mass activity after training. *Neuropsychologia*, *51*(5), 990–1001.

Hilton, C. B., Moser, C. J., Bertolo, M., Lee-Rubin, H., Amir, D., Bainbridge, C. M., Simson, J., Knox, D., Glowacki, L., Alemu, E., Galbarczyk, A., Jasienska, G., Ross, C. T., Neff, M. B., Martin, A., Cirelli, L. K., Trehub, S. E., Song, J., Kim, M., . . . Mehr, S. A. (2022). Acoustic regularities in infant-directed speech and song across cultures. *Nature Human Behaviour*, *6*(11), 1545–1556. https://doi.org/10.1038/s41562-022-01410-x

Hochmann, J.-R., & Kouider, S. (2022). Acceleration of information processing en route to perceptual awareness in infancy. *Current Biology*, *32*, 1206–1210.

Hykin, J., Moore, R., Duncan, K., Clare, S., Baker, P., Johnson, I., Bowtell, R., Mansfield, P., & Gowland, P. (1999). Fetal brain activity demonstrated by functional magnetic resonance imaging. *The Lancet*, *354*(9179), 645–646.

Joliot, M., Ribary, U., & Llinas, R. (1994). Human oscillatory brain activity near 40 Hz coexists with cognitive temporal binding. *Proceedings of the National Academy of Sciences, USA*, *91*(24), 11748–11751.

Khan, S., Vasung, L., Marami, B., Rollins, C. K., Afacan, O., Ortinau, C. M., Yang, E., Warfield, S. K., & Gholipour, A. (2019). Fetal brain growth portrayed by a spatiotemporal diffusion tensor MRI atlas computed from in utero images. *NeuroImage*, *185*, 593–608.

Khazipov, R., Khalilov, I., Tyzio, R., Morozova, E., Ben-Ari, Y., & Holmes, G. L. (2004). Developmental changes in GABAergic actions and seizure susceptibility in the rat hippocampus. *European Journal of Neuroscience*, *19*(3), 590–600.

Kidokoro, H. (2021). Delta brushes are not just a hallmark of EEG in human preterm infants. *Pediatrics International*, *63*(2), 130–136.

Kondaurova, M. V., & Bergeson, T. R. (2011). The effects of age and infant hearing status on maternal use of prosodic cues for clause boundaries in speech. *Journal of Speech, Language, and Hearing Research*, *54*, 740–754.

Kondaurova, M. V., Bergeson, T. R., & Xu, H. (2013). Age-related changes in prosodic features of maternal speech to prelingually deaf infants with cochlear implants. *Infancy*, *18*(5), 825–848.

Kravitz, E., Kuffler, S., & Potter, D. (1963). Gamma-aminobutyric acid and other blocking compounds in crustacea: Iii. their relative concentrations in separated motor and inhibitory axons. *Journal of Neurophysiology*, *26*(5), 739–751.

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

Lecanuet, J.-P., & Granier-Deferre, C. (1993). Speech stimuli in the fetal environment. In B. Boysson-Bardies, S. Schonen, P. Jusczyk, P. McNeilage, & J. Morton (Eds.), *Developmental neurocognition: Speech and face processing in the first year of life* (pp. 237–248). Springer.

Lee, C. S., Kitamura, C., Burnham, D., & McAngus Todd, N. P. (2014). On the rhythm of infant-versus adult-directed speech in Australian English. *The Journal of the Acoustical Society of America*, *136*(1), 357–365.

Leong, V., & Goswami, U. (2015). Acoustic-emergent phonology in the amplitude envelope of child-directed speech. *PLOS ONE*, *10*(12), Article e0144411. https://doi.org/10.1371/journal.pone.0144411

Leong, V., Kalashnikova, M., Burnham, D., & Goswami, U. (2017). The temporal modulation structure of infant-directed speech. *Open Mind*, *1*(2), 78–90. https://doi.org/10.1162/OPMI_a_00008

Le Van Quyen, M., Khalilov, I., & Ben-Ari, Y. (2006). The dark side of high-frequency oscillations in the developing brain. *Trends in Neurosciences*, *29*(7), 419–427.

Lovcevic, I., Kalashnikova, M., & Burnham, D. (2020). Acoustic features of infant-directed speech to infants with hearing loss. *The Journal of the Acoustical Society of America*, *148*(6), 3399–3416.

ManyBabies Consortium. (2020). Quantifying sources of variability in infancy research using the infant-directed-speech preference. *Advances in Methods and Practices in Psychological Science*, *3*(1), 24–52. https://doi.org/10.1177/2515245919900809

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.

Menn, K. H., Michel, C., Meyer, L., Hoehl, S., & Männel, C. (2022). Natural infant-directed speech facilitates neural tracking of prosody. *NeuroImage*, *251*, Article 118991. https://doi.org/10.1016/j.neuroimage.2022.118991

Menn, K., Männel, C., & Meyer, L. (2022). Early acquisition of phonological categories depends on the duration of features in speech. PsyArxiv. https://doi.org/10.31234/osf.io/29dek

Menn, K. H., Ward, E., Braukmann, R., van den Boomen, C., Buitelaar, J., Hunnius, S., & Snijders, T. M. (2022). Neural tracking in infancy predicts language development in children with and without family history of autism. *Neurobiology of Language*, *3*(3), 495–314. https://doi.org/10.1162/nol_a_00074

Mesgarani, N., Cheung, C., Johnson, K., & Chang, E. F. (2014). Phonetic feature encoding in human superior temporal gyrus. *Science*, *343*(6174), 1006–1110. https://doi.org/10.1126/science.1245994

Meyer, L. (2018). The neural oscillations of speech processing and language comprehension: State of the art and emerging mechanisms. *European Journal of Neuroscience*, *48*(7), 2609–2621.

Moghimi, S., Shadkam, A., Mahmoudzadeh, M., Calipe, O., Panzani, M., Edalati, M., Ghorbani, M., Routier, L., & Wallois, F. (2020). The intimate relationship between coalescent generators in very premature human newborn brains: Quantifying the coupling of nested endogenous oscillations. *Human Brain Mapping*, *41*(16), 4691–4703. https://doi.org/10.1002/hbm.25150

Moon, C., Cooper, R. P., & Fifer, W. P. (1993). Two-day-olds prefer their native language. *Infant Behavior and Development*, *16*(4), 495–500.

Muenssinger, J., Matuz, T., Schleger, F., Kiefer-Schmidt, I., Goelz, R., Wacker-Gussmann, A., Birbaumer, N., & Preissl, H. (2013). Auditory habituation in the fetus and neonate: An fMEG study. *Developmental Science*, *16*(2), 287–295.

Nacar Garcia, L., Guerrero-Mosquera, C., Colomer, M., & Sebastian-Galles, N. (2018). Evoked and oscillatory EEG activity differentiates language discrimination in young monolingual and bilingual infants. *Scientific Reports*, *8*(1), Article 2770. https://doi.org/10.1038/s41598-018-20824-0

Nallet, C., & Gervain, J. (2021). Neurodevelopmental preparedness for language in the neonatal brain. *Annual Review of Developmental Psychology*, *3*, 41–58.

Narayan, C. R., & McDermott, L. C. (2016). Speech rate and pitch characteristics of infant-directed speech: Longitudinal and cross-linguistic observations. *The Journal of the Acoustical Society of America*, *139*(3), 1272–1281.

Nazzi, T., Jusczyk, P. W., & Johnson, E. K. (2000). Language discrimination by English-learning 5-month-olds: Effects of rhythm and familiarity. *Journal of Memory and Language*, *43*(1), 1–19.

Nazzi, T., & Ramus, F. (2003). Perception and acquisition of linguistic rhythm by infants. *Speech Communication*, *41*(1), 233–243. https://doi.org/10.1016/S0167-6393(02)00106-1

Newman, R. S., Rowe, M. L., & Ratner, N. B. (2016). Input and uptake at 7 months predicts toddler vocabulary: The role of child-directed speech and infant processing skills in language development. *Journal of Child Language*, *43*(5), 1158–1173.

Nourski, K. V., Steinschneider, M., Rhone, A. E., Oya, H., Kawasaki, H., Howard, M. A., & McMurray, B. (2015). Sound identification in human auditory cortex: Differential contribution of local field potentials and high gamma power as revealed by direct intracranial recordings. *Brain and Language*, *148*, 37–50. https://doi.org/10.1016/j.bandl.2015.03.003

Ortiz-Mantilla, S., Hämäläinen, J. A., Musacchia, G., & Benasich, A. A. (2013). Enhancement of gamma oscillations indicates preferential processing of native over foreign phonemic contrasts in infants. *Journal of Neuroscience*, *33*(48), 18746–18754.

Ortiz-Mantilla, S., Hämäläinen, J. A., Realpe-Bonilla, T., & Benasich, A. A. (2016). Oscillatory dynamics underlying perceptual narrowing of native phoneme mapping from 6 to 12 months of age. *Journal of Neuroscience*, *36*(48), 12095–12105.

O'Shaughnessy, D. (1995). Timing patterns in fluent and disfluent spontaneous speech. *International Conference on Acoustics, Speech, and Signal Processing*, *1*, 600–603.

Owens, D. F., Boyce, L. H., Davis, M. B., & Kriegstein, A. R. (1996). Excitatory GABA responses in embryonic and neonatal cortical slices demonstrated by gramicidin perforated-patch recordings and calcium imaging. *Journal of Neuroscience*, *16*(20), 6414–6423.

Owens, D. F., Liu, X., & Kriegstein, A. R. (1999). Changing properties of GABAA receptor–mediated signaling during early neocortical development. *Journal of Neurophysiology*, *82*(2), 570–583.

Partanen, E., Pakarinen, S., Kujala, T., & Huotilainen, M. (2013). Infants' brain responses for speech sound changes in fast multifeature MMN paradigm. *Clinical Neurophysiology*, *124*(8), 1578–1585.

Peelle, J. E., Gross, J., & Davis, M. H. (2013). Phase-locked responses to speech in human auditory cortex are enhanced during comprehension. *Cerebral Cortex*, *23*(6), 1378–1387.

Peña, M., Pittaluga, E., & Mehler, J. (2010). Language acquisition in premature and full-term infants. *Proceedings of the National Academy of Sciences, USA*, *107*(8), 3823–3828.

Peña, M., Werker, J. F., & Dehaene-Lambertz, G. (2012). Earlier speech exposure does not accelerate speech acquisition. *Journal of Neuroscience*, *32*(33), 11159–11163.

Pivik, R., Andres, A., Tennal, K. B., Gu, Y., Downs, H., Bellando, B. J., Jarratt, K., Cleves, M. A., & Badger, T. M. (2019). Resting gamma power during the postnatal critical period for gabaergic system development is modulated by infant diet and sex. *International Journal of Psychophysiology*, *135*, 73–94.

Poeppel, D., & Assaneo, M. F. (2020). Speech rhythms and their neural foundations. *Nature Reviews Neuroscience*, *21*(6), 322–334.

Purpura, D. P., Girado, M., & Grundfest, H. (1957). Selective blockade of excitatory synapses in the cat brain by γ-aminobutyric acid. *Science*, *125*(3259), 1200–1202.

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.

Ramus, F. (2002). Language discrimination by newborns: Teasing apart phonotactic, rhythmic, and intonational cues. *Annual Review of Language Acquisition*, *2*(1), 85–115.

Raneri, D., Holzen, K. V., Newman, R., & Ratner, N. B. (2020). Change in maternal speech rate to preverbal infants over the first two years of life. *Journal of Child Language*, *47*, 1263–1275. https://doi.org/10.1017/S030500091900093X

Richards, S., & Goswami, U. (2015). Auditory processing in specific language impairment (SLI): Relations with the perception of lexical and phrasal stress. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1292–1305.

Routier, L., Mahmoudzadeh, M., Panzani, M., Azizollahi, H., Goudjil, S., Kongolo, G., & Wallois, F. (2017). Plasticity of neonatal neuronal networks in very premature infants: Source localization of temporal theta activity, the first endogenous neural biomarker, in temporoparietal areas. *Human Brain Mapping*, *38*(5), 2345–2358. https://doi.org/10.1002/hbm.23521

Schaworonkow, N., & Voytek, B. (2021). Longitudinal changes in aperiodic and periodic activity in electrophysiological recordings in the first seven months of life. *Developmental Cognitive Neuroscience*, *47*, Article 100895. https://doi.org/10.1016/j.dcn.2020.100895

Soderstrom, M. (2007). Beyond babytalk: Re-evaluating the nature and content of speech input to preverbal infants. *Developmental Review*, *27*(4), 501–532. https://doi.org/10.1016/j.dr.2007.06.002

Soderstrom, M., Seidl, A., Nelson, D. G. K., & Jusczyk, P. W. (2003). The prosodic bootstrapping of phrases: Evidence from prelinguistic infants. *Journal of Memory and Language*, *49*(2), 249–267.

Spinelli, M., Fasolo, M., & Mesman, J. (2017). Does prosody make the difference? A meta-analysis on relations between prosodic aspects of infant-directed speech and infant outcomes. *Developmental Review*, *44*, 1–18.

Steinschneider, M., Nourski, K. V., Kawasaki, H., Oya, H., Brugge, J. F., & Howard, M. A., III. (2011). Intracranial study of speech-elicited activity on the human posterolateral superior temporal gyrus. *Cerebral Cortex*, *21*(10), 2332–2347.

Takahashi, E., Folkerth, R. D., Galaburda, A. M., & Grant, P. E. (2012). Emerging cerebral connectivity in the human fetal brain: An MR tractography study. *Cerebral Cortex*, *22*(2), 455–464.

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. *Neuropsychologia*, *11*(4), 389–398.

Ter Schure, S., Junge, C., & Boersma, P. (2016). Discriminating non-native vowels on the basis of multimodal, auditory or visual information: Effects on infants' looking patterns and discrimination. *Frontiers in Psychology*, 7, Article 525. https://doi.org/10.3389/fpsyg.2016.00525

Tsuji, S., & Cristia, A. (2014). Perceptual attunement in vowels: A meta-analysis. *Developmental Psychobiology*, *56*(2), 179–191.

Tsurumi, S., Kanazawa, S., Yamaguchi, M. K., & Kawahara, J. (2021). Attentional blink in preverbal infants. *Cognition*, *214*, Article 104749. https://doi.org/10.1016/j.cognition.2021.104749

Vanhatalo, S., Tallgren, P., Andersson, S., Sainio, K., Voipio, J., & Kaila, K. (2002). DC-EEG discloses prominent, very slow activity patterns during sleep in preterm infants. *Clinical Neurophysiology*, *113*(11), 1822–1825.

Vecchierini, M.-F., André, M., & d'Allest, A. (2007). Normal EEG of premature infants born between 24 and 30 weeks gestational age: Terminology, definitions and maturation aspects. *Neurophysiologie Clinique/Clinical Neurophysiology*, *37*(5), 311–323.

Vosoughi, S., & Roy, D. K. (2012, May 22–25). *A longitudinal study of prosodic exaggeration in child-directed speech* [Paper presentation]. Speech Prosody, 6th International Conference, Shanghai, China.

Wakai, R. T., Leuthold, A. C., & Martin, C. B. (1996). Fetal auditory evoked responses detected by magnetoencephalography. *American Journal of Obstetrics and Gynecology*, *174*(5), 1484–1486.

Werker, J. F. (1995). Exploring developmental changes in cross-language speech perception. *An Invitation to Cognitive Science*, *1*, 87–106.

Werker, J. F., & McLeod, P. J. (1989). Infant preference for both male and female infantdirected talk: A developmental study of attentional and affective responsiveness. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *43*(2), 230–246. https://doi.org/10.1037/h0084224

Wu, Y. J., Hou, X., Peng, C., Yu, W., Oppenheim, G. M., Thierry, G., & Zhang, D. (2022). Rapid learning of a phonemic discrimination in the first hours of life. *Nature Human Behaviour*, *6*, 1169–1179.

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 and Experimental Neurology*, *70*(10), 841–858. https://doi.org/10.1097/NEN.0b013e31822f471c