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Final dissertation

Speech Perception in Congenitally Deaf Infants: An fNIRS Study

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0. Abstract

This study investigates the perception of native and unfamiliar languages in deaf and normal-hearing infants using functional near-infrared spectroscopy (fNIRS). It is hypothesized that there are significant differences in cortical activation patterns among healthy and deaf infants when exposed to forward Italian and English speech stimuli. Participants included preterm-born infants classified into two groups based on hearing capacities: 'normal hearing' and 'deaf' due to the existent hearing ability of fetuses starting from around the 27th week of gestation. Results revealed distinct cortical activation patterns between deaf and normal-hearing infants, with the deaf group exhibiting differentiated neural mechanisms in response to auditory deprivation. Findings highlight the dynamic nature of early brain development and emphasize the importance of tailored interventions for optimizing language acquisition, particularly in vulnerable populations. By elucidating the neural mechanisms underlying language perception in infancy, this study contributes to the understanding of language development and informs evidence-based interventions for promoting cognitive development and linguistic outcomes in early childhood.

1. Intoroduction

Investigating the foundations of speech perception in infants presents a complex yet critical endeavor in understanding the nexus of auditory development and language acquisition. The journey of language acquisition begins even before birth, as infants are exposed to a symphony of sounds in utero, shaping their emerging auditory capabilities. However, this developmental process can be significantly influenced by various factors, including impaired auditory experiences encountered in utero. Deafness and preterm birth represent two distinct challenges that can disrupt the typical auditory development of infants. Deaf infants, unable to perceive auditory stimuli in the conventional sense, face unique obstacles in navigating the auditory world and acquiring language. On the other hand, preterm infants, born prematurely, often undergo auditory experiences in the neonatal intensive care unit (NICU), which may differ markedly from those in utero, potentially impacting their subsequent speech perception abilities. Recent neuroimaging techniques, such as functional near-infrared spectroscopy (fNIRS), have provided unprecedented opportunities to investigate the neural underpinnings of speech perception in infants. This thesis delves into the impact of impaired auditory experiences in utero, particularly focusing on deafness and preterm birth, on postnatal speech perception capabilities. Leveraging the advanced capabilities of fNIRS, this research aims to provide a comparative analysis between deaf infants and their healthy counterparts. By employing fNIRS, it is aimed to unreveal the nuances of how early auditory deficits influence the trajectory of language acquisition and neural development associated with speech processing.

2. Near-Infrared Spectroscopy (NIRS)

Thanks to the improvement of technological methods in the mid-1990s, it is now possible to gather empirical knowledge about language abilities and their neural foundations. Near-infrared spectroscopy (NIRS) or optical topography (OT) has emerged as a valuable neuroimaging technique in language studies, offering a unique window into the cerebral hemodynamic changes associated with linguistic processing. NIRS exploits the near-infrared range of the electromagnetic spectrum to measure changes in blood oxygenation and hemodynamics in the cortical tissue. Neurons in brain regions performing specific cognitive tasks change their metabolic needs, leading to increased cerebral blood flow and oxygen delivery, thereby reducing deoxygenated hemoglobin (Babiloni et al., 2009). In the context of language research, NIRS provides real-time information about regional cerebral oxygenation levels, allowing for the assessment of cortical activation patterns during language tasks. Moreover, functional near-infrared spectroscopy (fNIRS) aims to pinpoint the brain networks involved in various behaviors by examining differences in brain activity during distinct states (Crosson et al., 2010).

When non-invasively measuring the hemodynamic response of the brain through the head, light must traverse multiple layers of biological tissue (including skin, skull, cerebrospinal fluid, etc.) before reaching the cortex, making tissue thickness a crucial parameter for determining penetration depth, accessible brain areas, and the magnitude of the obtained signal. Notably, newborns and young infants exhibit significantly thinner skin and skull compared to adults, resulting in a threefold increase in penetration from 3–5 mm to 10–15 mm into the cortex (Gervain et al., 2011). Thus, NIRS has found utility in monitoring cerebral oxygenation in neonatal studies due to the thickness of neonates' skulls. Besides, major advancements in the last decade, including the miniaturization of hardware, standardization of analysis methods, increased accessibility of hardware, and a shift towards imaging

techniques, have solidified fNIRS as a dependable and useful tool for research. (Highton et al., 2023).

2.1 Working Principle of NIRS

NIRS functions by emitting visible red and/or near-infrared light, typically between 650 and 2500 nanometers (nm), into the target tissue, such as the brain. It relies on the principle that biological tissues exhibit distinct absorption characteristics for near-infrared light. This light interacts with chromophores within the tissue, primarily hemoglobin, which has distinct absorption characteristics for different wavelengths of near-infrared light. The diffusely reflected light is then detected by optical detectors on the skin surface, and the intensity at various wavelengths is measured. Through spectroscopic analysis, the concentrations of oxygenated (OxyHb) and deoxygenated (DeoxyHb) hemoglobin are calculated, providing insights into changes in tissue oxygenation and blood flow. A surge in regional cerebral blood flow is prompted by the activation of astrocytes, as compared to neuronal activation. Consequently, a localized alteration occurs in the concentration of OxyHb andDeoxyHb in blood, both of which are principal absorbers of near-infrared (NIR) light in brain tissue. The spatial distribution of NIR light through various tissue layers forms a banana-shaped region, and achieving an optimal NIR light penetration depth, approximately half of the source-detector distance, is feasible with source-detector distances of 2–3 cm for infant head and 4–5 cm for adult head (Quaresima et al., 2012). In addition to the source–detector separation, wavelength and laser power also contribute to the quality of the NIRS signals (Gervain et al., 2011). However, the brain consistently maintains a state of dynamic equilibrium, characterized by baseline levels of measurable biochemical, electrophysiological, and cognitive elements. Any alterations in the baseline activation levels

resulting from stimulation can lead to temporal changes in one or more of these components within specific brain areas.

Changes in the concentration of hemoglobin levels are presumed to underlie the foundation of functional magnetic-resonance imaging (fMRI) blood oxygen level-dependent (BOLD) contrast. As a result, BOLD contrast is anticipated to exhibit a correlation with fNIRS measurements of OxyHb and DeoxyHb. In comparison to fMRI, fNIRS operates silently and is more tolerant to subtle movement artifacts, permitting activities such as overt speech, it can measure both OxyHb and DeoxyHb. It provides a more comprehensive evaluation of cortical hemodynamic response, it allows for long-time continuous measurements and repeated assessments within short intervals, and it boasts a higher temporal resolution, therefore, fNIRS is particularly well-suited for research involving infants (Quaresima et al., 2012).

2.2 NIRS in Language Studies

Despite its limited penetration depth, NIRS stands out as a versatile and valuable tool for non-invasive tissue assessment in scientific and medical research. Besides, due to the numerous disadvantages and inconvenience of other imaging tools in infants, the NIRS technique has become a useful and frequently used tool for studying language acquisition: the non-invasiveness, tolerance to motion, portability, real-time monitoring capabilities, safety, versatility, and accessibility of NIRS make it an ideal choice for investigating the neural underpinnings of language development in infants. Studies that used NIRS have provided valuable information about lateralization (Bortfeld et al., 2007, 2009; Gallagher et al., 2007; Gervain, 2015; Gervain et al., 2008; Kahlaoui et al., 2007; Kennan et al., 2002; May et al., 2011; Minagawa-Kawai et al., 2007, 2011a, 2011d; Obrig, 2010; Paquette et al., 2015; Peña et al., 2003; Perani et al., 2011; Quaresima et al., 2002, 2005; Sato et al., 2010, 2011, 2012; Taga et al., 2007; Taga & Asakawa, 2007; Telkemeyer et al., 2009; Watson et al., 2004; Watanabe

et al., 1998), language recognition (Peña et al., 2003; Minagawa-Kawai et al., 2002), prosodic discrimination (Grossmann et al., 2010; Homae et al., 2007; Saito et al., 2007b), linguistic sequences (Benavides-Varela & Gervain, 2017), word fluency (Matsuo et al., 2000; Quaresima et al., 2005; Watson et al., 2004; Watanabe et al., 1998), speech perception (Gervain & Mehler, 2010; Peña et al., 2003; Saito et al., 2007a, 2007b), signal processing (Zhang et al., 2017), social cognition (Blasi et al., 2007; Csibra et al., 2004; Grossmann et al., 2008; Grossmann & Johnson, 2014; Lloyd-Fox et al., 2009; Nakato et al., 2009; Otsuka et al., 2007), multi-sensory processing (Bortfeld et al., 2007, 2009; Taga & Asakawa, 2007) and cortical activation to auditory stimuli (Bortfeld et al., 2007; Chen et al., 2002; Minagawa-Kawai et al., 2011b; Sakatani et al., 1999; Taga & Asakawa, 2007; Zaramella et al., 2001).

2.3 Advantages

In language studies, neuroimaging techniques possess considerable potential in discerning and capturing cortical activities specifically associated with language processing, offering a nuanced understanding of the intricate neural dynamics involved in linguistic functions (Minagawa-Kawai et al., 2007; Minagawa-Kawai et al., 2008). In this context, NIRS brings its unique benefits by emerging as a versatile and valuable optical imaging technique, offering a multitude of advantages across diverse fields such as neuroscience, physiology, clinical medicine, and linguistic studies. (1) NIRS is non-invasive, meaning it does not require surgery or the introduction of exogenous agents, making it safer for human subjects; (2) it provides continuous and real-time measurements, allowing researchers and clinicians to observe changes in tissue parameters immediately; (3) NIRS systems are often compact and portable, enabling use in various settings, including bedside monitoring, field research, and ambulatory applications; (4) near-infrared light used in NIRS is non-ionizing and considered

safe for biological tissues, making it suitable for repeated measurements without harmful effects; (5) NIRS can be applied to study various tissues and organs, including the brain, muscles, and internal organs, offering versatility in different scientific disciplines; (6) it allows for quantitative assessment of tissue oxygenation, blood volume, and other physiological parameters, providing valuable information for researchers and healthcare professionals; (7) patients typically experience minimal discomfort during NIRS measurements, contributing to better participant compliance in research studies and clinical applications; (8) NIRS can capture changes in baseline levels, providing insights into the dynamic equilibrium of biochemical, electrophysiological, and cognitive elements in tissues; (9) in contrast to some imaging techniques, NIRS operates silently, making it suitable for studying activities like overt speech without interference; (10) particularly in comparison to certain imaging modalities, NIRS offers high temporal resolution, allowing researchers to capture rapid physiological changes over short time intervals.

2.4 Limitations

The investigation of cortical hemodynamic responses to cognitive stimuli involving deep brain regions like the basal ganglia and amygdala is hindered by the limitations of fNIRS, which is restricted to the outer cortex with a typical depth sensitivity of 1.5 cm, making the separation of NIRS signals from cerebral and extracerebral tissues challenging (Gervain et al., 2011; Quaresima et al., 2012). Secondly, compared to certain imaging modalities like fMRI, NIRS generally exhibits lower spatial resolution: this might result in a limitation when it comes to precisely localizing neural activity within the brain. Researchers and clinicians using NIRS may face challenges in identifying specific brain regions with high precision, which could be crucial for certain types of studies or medical diagnoses. The absolute quantification of fNIRS measures using Continuous Wave (CW) systems is impeded by their

inability to measure optical path length, requiring consideration of optical path length variations across head regions; furthermore, the wavelength dependence of optical tissue properties introduces a wavelength-dependent partial volume effect, potentially causing changes in one chromophore concentration to mimic the effects of another (Minagawa-Kawai et al., 2008). Convergence between infant and adult language studies is anticipated to be lacking due to distinct hemodynamic responses resulting from the infant's immature vascular regulation and variations in light scattering and absorption in the immature brain (Quaresima et al., 2012). The penetration depth of near-infrared light is limited, usually up to a few centimeters beneath the skin. This restricts the investigation of deeper brain structures and is a significant limitation in certain applications, as well as, the wavelength dependence of optical tissue properties can lead to a partial volume effect, making it challenging to differentiate changes in one chromophore concentration from another, particularly in complex brain regions.

3. Language Development

The exploration of speech and language processing in infants offers an intriguing insight into the cognitive and developmental mechanisms underpinning precocious language acquisition. From very early stages, infants show a natural ability for language processing, a crucial skill for the complex task of learning to speak. This early stage of language development involves quickly picking up sounds, grammar rules, and meanings from their surroundings, showing the impressive adaptability of the infant brain. Research in this area has consistently emphasized the important times when exposure to language has the most impact, revealing that even the youngest children are equipped to easily process sound patterns in language. This early ability to grasp language not only influences their immediate ability to communicate but also affects their future cognitive and language skills. Comprehending these natural language skills in infants is important not just for developmental psychology and linguistics but also for creating effective support strategies for young children exhibiting atypical language development trajectories.

3.1 Linguistics and Speech Perception

All languages adhere to hierarchical principles, established by specific rules in each language, necessitating the identification of individual words, phrases, and sentences for the decoding of speech, a process initially guided by acoustic cues during language acquisition (Minagawa-Kawai et al., 2007). During the initial stages of language learning, particularly in infancy, this decoding process is heavily guided by acoustic cues (Obrig, 2010) such as intonation, rhythm, stress, and pitch. The ability to identify and differentiate these linguistic units is a fundamental aspect of language development. Therefore, language acquisition is not only about learning a collection of words but also about mastering the intricate patterns and rules that give a language its unique structure and meaning.

Speech processing follows a sequence that begins with the acoustic analysis, encompassing both segmental (phonemic) and suprasegmental (prosodic) elements like intonation and stress, leading to lexical access, syntactic integration, and ultimately, semantic interpretation, with specific acoustic and language properties, such as temporal versus spectral details and native versus nonnative speech patterns, influencing the pattern of neural recruitment and hemispheric dominance (Best & Avery, 1999; Dehaene-Lambertz et al., 2005; Gandour et al., 2002; Poeppel, 2003; Pulvermüller et al., 2005; Obrig., 2010). For instance, the phonemes specific to a person's native language are primarily processed in the left hemisphere of the auditory area, while the right hemisphere preferentially handles the processing of suprasegmentals, or nonlexical prosody (Minagawa-Kawai et al., 2007). The lateralization process for individual acoustic/phonological properties, language-specific contrasts, and other singular features may require an extended duration, reflecting the developmental shift in language perception during the initial year of life: this shift progresses from general, broad-based abilities to heightened sensitivity towards the specific characteristics of the native language, a phenomenon referred to as perceptual attunement (Gervain et al., 2011) as found the left lateralization for the short–long vowel contrast becomes prominent as the perception of the contrast undergoes refinement, transitioning from a basic acoustic difference to a phonological property relevant to the language (Minagawa-Kawai et al., 2007).

3.2 Lateralization

Lateralization research has gained prominence in the realm of linguistic studies, offering substantial insights into the anatomical underpinnings and functionality of language processing mechanisms. The human cerebral hemispheres display notable structural asymmetry. In the infant's brain, language organization is widespread and bilateral, but as age increases, it becomes more lateralized to the left hemisphere (Vandormael et al., 2019). At the

age of 3 months, speech perception becomes predominantly left-lateralized, with noticeable activity occurring in the superior temporal gyrus and the angular gyrus (Dehaene-Lambertz et al., 2002). In detail, the human brain at birth presents a left temporal area dominant response to the native language (Vannasing et al., 2016), a right temporal area response to a rhythmically different language (Vannasing et al., 2016), and a bilateral temporal area response to non-linguistic stimuli (Vannasing et al., 2016; Dehaene-Lambertz et al., 2010). In time, with sensory experience, all language responses in the brain shift to the left hemisphere (Vandormael et al., 2019). Structural asymmetries observed early in perisylvian regions such as the heschl gyrus, planum temporale, and superior temporal sulcus, are evident in the fetal (Dubois et al., 2008a; Dubois et al., 2010) and preterm-brain (Dubois et al., 2008b). Such asymmetry, as noted by Dubouis et al. (2010) and Dehaene-Lambertz et al. (2002), may signal functional divergence in language processing. Correspondingly, at birth, the brain shows a high degree of specialization in speech response, with activation observed in anterior temporal regions for both familiar and unfamiliar languages, but not for non-linguistic sounds (Dehaene-Lambertz et al., 2010; Kotilahti et al., 2010; May et al., 2017; Vannasing et al., 2016). This indicates that newborn infants possess an innate sensitivity to certain temporal aspects of speech stimuli (Pena et al., 2003). Besides, structural MRI analyses have revealed asymmetries in the brain's left hemisphere language regions present from birth (Dubois et al., 2010). Therefore, it can be said that, in addition to its anatomical complexity, the human brain is functionally organized to language processing in the left hemisphere (Kotilahti et al., 2010; Mehler & Dupoux, 1994; Norrelgen et al., 2012; Paquette et al., 2015; Peña et al., 2003; Szaflarski et al., 2006).

Left hemisphere dominance in language processing has been shown in different studies with infants (Dehaene-Lambertz et al., 2002; Dehaene-Lambertz et al., 2010; Dubois et al., 2010; Gervain et al., 2008; Minagawa-Kawai et al., 2011a; Peña et al., 2003; Sato et al., 2012),

however, speech perception is not universally left-lateralized (Minagawa-Kawai et al., 2011a) because the conceptualization of language as a unilateral process is overly simplistic (Tab. 1), such as from the neonatal stage, the right hemisphere is already specialized in prosody processing (Arimitsu et al., 2011). On the one hand, Vannasing and colleagues (2016) observed neonates within the first 24 hours post-birth in a pronounced predilection for the processing of native language within the left temporal area, as opposed to the right temporal area. This finding posits that the predominance of the left hemisphere in linguistic tasks is an innate characteristic, rather than a result of linguistic acquisition through learning experiences. In contrast, responses to non-native linguistic stimuli were predominantly observed in the right temporal region, surpassing activity in the left temporal region, particularly when contrasting maternal language processing with that of a foreign tongue, as delineated in the findings by Vannasing et al. (2016). Moreover, in a study employing NIRS, Minagawa-Kawai and colleagues (2011b) explored the neural underpinnings of language processing in 4-month-old Japanese infants. This study meticulously assessed how these infants' brains responded to a spectrum of auditory stimuli: their native language (Japanese), a foreign language (English), and a range of non-linguistic sounds including emotional human voices, calls of non-human primates (monkey calls), and scrambled speech patterns. The findings revealed a pronounced activation in the left hemisphere of the brain for both the familiar (Japanese) and unfamiliar (English) linguistic stimuli, as compared to the non-speech sounds. Significantly, the brain's response was more pronounced when infants were exposed to the familiar Japanese language than to English. This differential activation suggests a heightened neural sensitivity to the phonetic and prosodic elements of the native language. Furthermore, the study illuminates the developing linguistic brain's ability to differentiate between speech and non-speech sounds, underscoring the early specialization of the left hemisphere in processing language. In contrast, May and colleagues (2017) found that

neonates showed a bilateral forward advantage when processing their native language (English) as compared to an unfamiliar language (Spanish) which is a controversial result to previous the studies mentioned above. Differences in the acoustic and phonological attributes of the languages examined might account for these discrepancies, suggesting that newborn brains are inherently geared towards processing native language speech, a specialization further refined by linguistic experiences and phonological nuances (Zhang et al., 2022). Briefly, language processing is a complex operation, and it requires different systems and hemispheres to work as a unit. Further research is needed to better understand lateralization in language.

Table 1

Hemispheric representations of language components.

Component	Definitions	Structural Aspect	Functional Aspect	LH	RH
Phonological	Related to the language sounds	X		X	
Morphologic	Related to morphemes - smaller meaningful units - that build up words	X		X	
Syntactic	Related to sentence organization	X		X	
Semantic	Related to the meaning of linguistic units: literal (LH) and nonliteral (RH)	X	X	X	X
Pragmatic	Related to the interlocutors' communicative intentions		X		X

Note. Data from Fonseca, Scherer, Oliveira & Parente (2009).

3.3 Prenatal and Postnatal Experience

Fetuses' prenatal experience with language mainly consists of prosody, which thus becomes a fundamental guiding principle for infants' speech processing (Gervain, 2018). The developmental trajectory of human auditory perception starts substantially before birth, within the prenatal environment. This critical phase of auditory development is instrumental in shaping an infant's subsequent communicative abilities and interaction with their

surroundings. Thus, infants begin acquiring knowledge of the prosodic patterns of their native language before birth, and following delivery, they leverage this prosodic understanding to distinguish their native language from other environmental sounds and to parse the continuous speech stream into linguistically meaningful units. Hearing starts to develop around the 18th week of gestation, and the cochlea reaches its adult size by the 25th week (Bibas et al., 2007). It continues to develop until full term, and low-frequency sounds are responded by fetuses around 26th week (Hepper & Shahidullah, 1994; Smith et al., 1990), and to low-pitched sounds in the late third trimester of pregnancy (Lecanuet et al., 2000) promoting language acquisition. The initial exposure of infants to language in the womb involves a limited, low-pass filtered signal primarily conveying prosodic information (Gervain, 2018). In line with this, fetuses show various auditory abilities. They exhibit voice recognition: fetuses can discriminate their mother's voices (Kisilevsky et al., 2003) and foreign languages (Kisilevsky et al., 2009); they can discriminate between different pure tone acoustic stimuli and speech sounds (Draganova et al., 2007; Hepper & Shahidullah, 1994); they can perceive and discriminate segmented speech sounds (Groome et al., 1999), sound streams and rapid temporal variations in amplitude specific to speech sounds (Granier-Deferre et al., 2011); they can also discriminate the change in different gender sounds (Lecanuet et al., 1993). Essentially, humans come into the world with a brain structure primed to recognize speech signals and focus on the spoken expressions present in their environment (Peña et al., 2003).

Traditionally, languages are grouped into three primary rhythmic types: stress-timed languages like English and Dutch, syllable-timed languages such as Italian and French, and mora-timed languages, examples being Japanese. Understanding these distinctions is essential for establishing the basics of prenatal language acquisition. Therefore, the observable preference for specific languages in infants can often be attributed to these rhythmic patterns.

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Newborn infants are capable of discerning between forward and backward speech patterns, and they also can recognize the difference between their mother tongue and foreign languages based on unique rhythmic characteristics, like the stress-timed rhythm found in languages such as English and German, in contrast to the syllable-timed rhythm typical of languages like French and Spanish (Mehler et al., 1988). Namely, neonates can discriminate rhythmically in different languages (Mehler et al., 1988; Nazzi et al., 1998; Ramus et al., 2000; Ramus, 2002) which stands to the fact that babies in the womb are exposed to language spoken in the outside world. This discrimination ability may suggest that it is based on particular properties of speech (Byers-Heinlein et al., 2010), and not applicable to just any patterned complex sound (Vouloumanos & Werker, 2007). Moreover, newborn infants can discriminate utterances in their native language from those in an unfamiliar language (Mehler et al., 1988; Moon et al., 1993) which is also evident in bilingual newborns who can discriminate between two rhythmically different languages whose mothers speak during pregnancy (Byers-Heinlein et al., 2010). Moreover, Moon and colleagues (2013) showed that newborn infants could discriminate subtle differences in sounds of the same vowel in two languages. They can discriminate between their mother's voice and the voice of other women (Fifer & Moon, 1995) and show preference for their mother's voice immediately after birth (DeCasper & Fifer, 1980). Neonates can distinguish female and male voices (DeCasper & Prescott, 1984), and different frequencies of the same words (DeCasper & Spence, 1986). They use different neural oscillations for speech and non-speech processing (Dehaene et al., 1997; Dehaene-Lambertz et al., 2002; May et al., 2011; Peña et al., 2003) which is also evident in 3-months babies (Dehaene-Lambertz, 2002), and they are biased to listen to the speech compared to non-speech stimuli (Dehaene-Lambertz et al., 2010; Vouloumanos & Werker, 2007).

Byers-Heinlein and colleagues (2010) revealed how prenatal exposure to language determines the preference for language after birth. Newborn bilingual infants' attention to both languages is consistent with their having learned about two languages prenatally which means, regardless of number, language preference is influenced by the language(s) heard in the womb before the birth (Byers-Heinlein et al., 2010). However, having a preference for two languages does not imply confusion between them (Byers-Heinlein et al., 2010). The second procedure in the same study showed that both English monolingual newborns and Tagalog-English bilingual newborns could discriminate between English from Tagalog. The same perceptual and learning mechanisms that support acquisition in a monolingual environment thus also naturally support bilingual acquisition (Byers-Heinlein et al., 2010). Furthermore, Lillian May and colleagues (2011), empirically demonstrated by the research conducted by using NIRS to see how prenatal language experience might shape the brain response to language in newborn infants. They tested 20 monolingual prenatally English-exposed neonates' neural responses by hearing low-pass filtered sentences of forward English (familiar language), forward Tagalog (unfamiliar language), and backward English and Tagalog (non-language). Consequently, neonates showed greater hemispheric response in forward English sentences compared to forward Tagalog ones, and they showed similar neural responses to backward English and backward Tagalog. This is the first study to use filtered speech in a neuroimaging study addressing prenatal experience in language response and provides important evidence about how prenatal experience with the language learned by a newborn in the womb influences how their brain responds to language across regions sensitive to speech processing (May et al., 2011). These results show that infants confront language already in the fetal period in the womb (Benavides-Varela et al., 2011; Gervain, 2018; May et al., 2011; May et al., 2017), however, the origins and developmental path of the

neural underpinnings associated with speech and language processing in infancy are not fully elucidated yet (Zhang et al., 2022).

3.4 Developing Brain

In the months following birth, infants experience remarkable brain maturation and developmental changes, particularly in the realms of hearing and language processing. This phase is characterized by rapid neural growth and the establishment of crucial neural pathways, facilitating the advancement from basic auditory perception to more intricate language processing skills, especially in terms of the critical period. As their sensory and cognitive systems mature, infants begin to exhibit an increased capacity for distinguishing and interpreting a wider range of auditory stimuli, a cornerstone in their linguistic and communicative development. These changes are not merely incremental; they represent significant leaps in the infant's ability to interact with and understand their environment. Starting from 4 months, infants can distinguish pitch accent patterns, and they exhibit undifferentiated responses to native language words and pure tone equivalents, indicating an early stage of primarily acoustic and nonlinguistic processing (Sato et al., 2010). In the stages of development, the brain undergoes changes in processing auditory stimuli. Grossman and colleagues (2010) presented that 4- to 7-month-old babies found increased responses in the left and right superior temporal cortex to human voice when compared to non-vocal sounds. This indicates that the brain systems sensitive to voices begin to develop between the ages of 4 and 7 months (Grossman et al., 2010). Furthermore, in their study, Zhang and colleagues (2022) have shown that neurodevelopmental changes in speech processing during the first year of life are present. Utilizing fNIRS, they investigated hemodynamic responses in the temporal cortex of seventy-eight infants at 5 and 10 months of age while they were exposed to forward speech in their native language -Dutch, and backward Dutch. They found that at 5

months of age, infants exhibit comparable auditory processing responses to both forward and backward speech, whereas by 10 months, they demonstrate the ability to differentiate between the two, displaying a more pronounced inverted left-lateralized response specifically to forward speech. This brought us to the conclusion that the alignment of infants with native speech induces a reorganization, prompting a shift from universal auditory processing to linguistic processing of speech, thereby molding specialized brain functions (Zhang et al., 2022). Another study (Peña et al., 2010) found that preterm infants at 6 months of age do not have discrimination ability to languages from the same rhythmic class as well as the full-term 3-month-old infants due to they have not attained sufficient brain maturation to recognize that the maternal language is separate from other rhythmically similar languages. Native language could be discriminated at 4 months of age (Bosh & Sebastián-Gallés, 1997; Grossman et al., 2010; Nazzi et al., 2000; Peña et al., 2010; Zhang et al., 2022) because neural substrate, which refers to the underlying neural structures and pathways responsible for auditory processing, is less mature in younger groups of both full-term and preterm infants (Peña et al., 2010). This immaturity is intricately linked to heightened neuroplasticity, signifying the brain's adaptability and its capacity for experience-dependent changes. The malleability of the auditory neural substrate in younger infants suggests a dynamic process of connection refinement, potentially shaping responses to auditory stimuli based on environmental experiences. The developmental disparities observed carry profound implications for sensory processing and learning, particularly in domains crucial to language acquisition, social interaction, and broader cognitive functions (Kral et al., 2016). Briefly, at the first stages of life, the maturation of neural networks assumes a pivotal role in facilitating language acquisition. The emphasis on the period between 4 and 10 months critical period (Grossman et al., 2010; Peña et al., 2010; Zhang et al., 2022) also sheds light on the potential for early detection and intervention strategies for developmental disorders. Consequently, it can be

suggested that the human brain is predisposed to prioritize and process human speech, which is crucial for language acquisition and social communication. The development of voice-sensitive regions in the during this critical period aligns with other developmental milestones in sensory and cognitive processing. This reflects the brain's remarkable ability to adapt and specialize in response to environmental stimuli, a phenomenon known as neuroplasticity. Moreover, the bilateral activation of the superior temporal cortex in response to voice, as opposed to non-vocal sounds, indicates that the processing of human speech is a complex, integrative function that engages multiple brain regions simultaneously. This complexity is integral to the development of sophisticated language skills later in life. These findings by Grossman et al. (2010), Sato et al. (2010), Peña et al. (2010), and Zhang et al. (2022) contribute to a broader understanding of the developmental trajectory of auditory processing in the brain. It highlights the period between 4 and 10 months as a crucial window for auditory-related neural development, potentially laying the foundation for future research into early interventions for speech and language disorders.

4. Hearing

Cognitive and physical development in early infancy is a complex and dynamic process. It involves a series of intricate neurobiological changes that lay the foundation for future learning and growth. In this context, it's important to understand the role of various developmental processes. In neurotypical children, ontogenetic events support the development of the brain through neurogenesis, axonal and dendritic growth, synaptogenesis, synaptic pruning, and myelination (Anderson et al., 2001). These occurrences are closely interconnected, meaning that disruptions in one specific aspect of development can lead to enduring impacts on the brain's structural and functional soundness (Grantham-McGregor et al., 2007). Alongside, the proper maturation of cognitive abilities and behaviors hinges critically on developments occurring intrauterine and in early childhood, a period where brain development is primarily characterized by the reorganization, 'fine-tuning,' or remodeling of primary circuits and networks after months of birth (Gilmore et al., 2018).

4.1 Development of the Auditory System

The development of the central nervous system for auditory processing is a complex and intricate process that plays a critical role in hearing. This system involves a network of cells, nuclei, and pathways that are responsible for the preservation and transfer of auditory information. When there is normal hearing in utero and postnatal period, the central nervous system in development allocates both space and organization structurally for the processing of auditory information that is vital for the effective handling of sound inputs (Kilgard et al., 2002). Sound waves are converted into electrical signals in the inner ear and transmitted to the brain via the auditory nerve. The ability to receive sensory information relies on the health of these specialized receptor cells, which encode physical stimuli and convert them for processing by the brain's information-processing system (Kral et al., 2016). Both animal

(Heid et al., 1997; Stakhovskaya et al., 2008) and human (Ahmed et al., 2018; Huang et al., 2002; Striem-Amit et al., 2016) studies showed that the fundamental wiring framework in the subcortical afferent auditory system which is responsible for processing and relaying auditory information from ears to the auditory cortex forms partially before the onset of hearing in utero. This early development is crucial as it lays the foundational wiring or neural pathways for auditory processing. The auditory system's basic structure and connections are formed during this period. Therefore, this fundamental wiring framework in the subcortical afferent auditory system is still maintained even in cases of deafness. When the auditory system effectively processes sound in utero, it allows for the accurate perception and interpretation of speech sounds, which is crucial for language acquisition and development, however, any disruptions or impairments in auditory processing can potentially lead to difficulties in language development, as the ability to perceive and discriminate between sounds is foundational for learning to understand and produce language. Following birth, due to auditory system requires stimulation to mature and maintains its plasticity throughout periods of profound deafness (Ponton et al., 1996), lacking auditory experiences during early growth stages impedes the functional advancement, causes a delay in the development of cortical synapses, and intensifies the elimination of these synapses later on (Kral & Sharma, 2012). This profoundly affects key central auditory functions, such as the coding of sound intensity, operation of cortical columns, spatial mapping of cochlear signals, auditory space perception, and intricate corticocortical interactions, encompassing both the hierarchical control mechanisms and the construction of auditory perceptions (Kral, 2013). Therefore, even if the auditory input is restored later in life, some aspects of the normal neural development necessary for auditory processing may have been permanently lost, making those resources no longer available for effective auditory processing (Sharma et al., 2002; Szagun, 2004).

4.2 Congenital Deafness

Congenital deafness refers specifically to hearing loss that is present at birth and it is characterized by disrupting the typical development of the auditory brain, leading to challenges in acquiring spoken language skills (Sharma & Campbell, 2011). Two out of every thousand newborns experience congenital deafness (Grégoire et al., 2022) making it the most prevalent disorder present at birth that can severely hinder the development of early communication skills because of the absence of auditory input (Dieleman et al., 2019). In typically developing infants, the ability to perceive speech sounds, the development of phonological skills, and the expansion of vocabulary are seen as fundamental cognitive-linguistic building blocks that form the foundation for later language comprehension and expression, as well as literacy (Jusczyk, 1997). Children with hearing loss experience impacts on their neurocognitive growth, affecting various areas such as hearing, language, cognition, social skills, reading and writing abilities, and overall academic performance (Fitzpatrick, 2015). Furthermore, the most evident and comprehensible consequence of congenital hearing loss is the interference with the normal process of acquiring spoken language (Fitzpatrick, 2015). Alongside, restricted access to language leads to hindered cognitive and socioemotional growth (Cheng & Mayberry, 2019), resulting in cognitive setbacks, mental health challenges, and a diminished quality of life (Hall, 2017). Further, the severity of hearing impairment significantly correlates with language skill development; children with severe hearing loss face a considerable risk of experiencing notable delays in speech and language development, which can subsequently impact their communication abilities, cognitive growth, and social development (Connor et al., 2006). In short, hearing loss, even a partial amount, leads to alterations in the brain, impacting units within the neural networks responsible for attention, cognitive control, and visual and sensorimotor regions (Wolak et al., 2019).

Hearing impairment varies in severity, from mild to profound levels (Tab. 2). Even though the majority of hearing loss cases are acquired later in life (Grégoire et al., 2022), the age onset influences brain function in distinct ways, highlighting the importance of sensitive periods in the development of the brain (Wolak et al., 2019). Additionally, the knowledge in the literature on hearing loss etiology influence on language outcome is limited and inconclusive. Although some studies have covered that the etiology of hearing impairment affects language outcome (Percy-Smith et al., 2013; Varga et al., 2014), strong evidence, also done in younger populations, referring the etiology of hearing impairment has an inconsiderable effect on language outcome do exist (Dieleman et al., 2019; Miyagawa et al., 2016; Nikolopoulos et al., 2006; Philips et al., 2014).

Table 2

Definitions of hearing loss characteristics

Congenital	Present at or very shortly after birth
Delayed-onset	Develops postnatally; cannot be attributed to an exogenous cause
Acquired	Develops postnatally; attributable to an exogenous cause
Early-onset	Develops within 3 months of birth
Prelingual	Develops before language is well established (<3 years of age)
Progressive	The auditory thresholds decline as time progresses.
Mild	PTA average (500, 1000, 2000 kHz) 20–40 dB HL
Moderate	PTA average 41–55 dB HL
Moderately severe	PTA average 56–70 dB HL
Severe	PTA average 71–90 dB HL
Profound	PTA >90 dB HL

Note. Data from Fitzpatrick (2015). Pure-tone average (PTA), and hearing level (HL).

4.2.1 Structural Brain Changes in Congenital Deafness

Reduced volume of white matter or lower fractional anisotropy in the auditory regions, typically observed in individuals deaf from birth, and structural changes in the frontal, visual, and other brain areas, including the cerebellum, are likely due to cross-modal plasticity resulting from the absence of sound input and the use of sign language instead of spoken language (see review of Hribar et al., 2020). Cross-modal plasticity refers to auditory cortical areas that are deprived of sound input and begin to process signals from other senses, such as vision and touch (Allman et al., 2009; Campbell and Sharma, 2014; Petitto et al., 2000). Yet, cross-modal reorganization might not always be beneficial and does not guarantee an enhancement of the dominant visual sense (Deroche et al., 2023). In their systematic review, Simon and colleagues (2020) identified key features of structural plasticity in congenitally or prelingually deaf individuals by examining cerebral changes in the gray and white matter by providing an up-to-date synthesis with a focus on structural changes with the following neuroimaging techniques using magnetic-resonance imaging (MRI): *volumetry, voxel-based morphometry, tensor-based morphometry, cortical thickness, diffusion tensor imaging,* and *diffusion kurtosis imaging* within 27 cross-sectional studies published between 2003 and 2017 that were selected that describe the structural changes reported in 626 individuals with a moderate-to-profound bilateral deafness, including 254 children and adolescents. They concluded by homogeneous results the primary auditory cortex (heschl's gyrus) bilaterally which is related to processing speech sounds, the secondary auditory cortex (planum-polare and planum-temporale), and the bilateral superior temporal gyrus showed a significant decrease in white matter volume and density as well as reduced fractional anisotropy. The superior temporal gyrus is frequently linked to structural changes observed in individuals who are deaf, making it the brain region most commonly associated with such modifications (Simon et al., 2020). Early absence of auditory stimulation leads to reduced myelination in

these areas. Attenuation in white matter volume and fractional anisotropy in the inferior frontal gyrus of the left hemisphere were also reported. In sum, they suggested significant changes in the main cortical and subcortical structures implicated in auditory processing, language-related areas that appear to be present from an early age and have long-lasting effects. In addition, Zhang and colleagues in 2015 heightened regional susceptibility in the superior temporal sulcus and cingulate areas, accompanied by an abnormal asymmetry in the right hemisphere in preterm-born children. In their meta-analysis study, Grégoire and colleagues (2022) showed that severe to profound deafness induces modifications of both brain white matter and gray matter characteristics mainly but not limited to the temporal lobe even though one-third of the studies did not find any significant modifications in brain anatomy. Hence, they concluded that the type and timing of language acquisition play a crucial role in shaping brain structure and function, with early language exposure being essential for the normal development of language areas in the brain, especially in the white matter bundles. Collectively, the changes in these white matter bundles might result from the lack of exposure to spoken language, the use of sign language, or possibly from early language deprivation in instances where there is a delayed diagnosis of deafness (Grégoire et al., 2022). These studies collectively highlight a crucial neural plasticity, particularly in the brain's auditory and language-processing regions. The consistent findings of reduced white matter volume and altered myelination patterns in key areas such as the superior temporal gyrus and primary auditory cortex underscore the profound impact of sensory deprivation on brain structure.

These changes are not only confined to the auditory regions but also extend to language-related areas, indicating the intricate relationship between sensory experience and brain development. The findings highlight the critical importance of early language exposure, whether auditory or through sign language, in shaping the brain's structural and functional

development. Briefly, neurosensory prosthetics have the potential to alleviate the impacts of sensory loss by restoring aspects of sensory function, yet the consequences of such loss extend significantly beyond the sensory system and its related brain functions, profoundly affecting central neurological and higher-order neurocognitive functioning (Kral et al., 2016). Therefore, understanding the dynamics of synaptic plasticity in the juvenile brain, and how the auditory system develops and is preserved in deafness are essential for fostering optimal cognitive and sensory growth during early childhood, and the neural basis of hearing and deafness.

4.3 Neuroplasticity

All members of a species have evolved to anticipate distinct environmental states and are inherently predisposed to develop various phenotypes in response to diverse environmental or somatic conditions, and this principle extends to developmental mechanisms, which are evolutionarily primed to generate continuous phenotypic variation, exemplified by adaptive calibration of maturation rates into nutritional conditions (Frankenhuis & Walasek, 2020). When engaged in auditory processing, the brain undertakes dual functions: initially, it analyzes sound by breaking it down into acoustic features, highlighting those crucial for distinguishing biologically significant sounds; subsequently, it categorizes these fundamental acoustic features into a resilient representation, forming an auditory object capable of withstanding the inherent variability within the sensory environment (Kral & Sharma, 2012). The juvenile brain quickly adjusts to its environment, making it particularly vulnerable to the loss of sensory input (Hübener & Bonhoeffer, 2014; Whiteus et al., 2013). The auditory system requires stimulation for maturation and retains its plasticity during profound deafness, while the reception of sensory information is contingent on the health of specialized receptor cells; furthermore, brain development, being a self-organizing process, means the

development of the connectome heavily relies on sensory experiences, making sensory loss akin to a connectome disorder like neurocognitive effects (Kral et al., 2016). For these reasons, auditory sensation and brain development in infants, the concept of neural plasticity, and its implications during sensitive periods are particularly significant. It is suggested that multiple sensitive periods exist during the development of the human auditory system, each pertaining to different language aspects such as auditory processing, phonetics, phonology, syntax, and semantics (Lenneberg, 1967; Ruben, 1997). During these sensitive periods (Kral et al., 2001), infants' brains are remarkably adapting to auditory stimuli, allowing for the efficient formation of synaptic connections related to hearing and sound interpretation because the juvenile brain exhibits a heightened capacity for plastic reorganization (Nakahara et al., 2004; Sale et al., 2009) a phenomenon largely attributed to developmental changes in the molecular machinery of synaptic plasticity (Morishita & Hensch, 2008; van Zundert et al., 2004) likely to support development that is fine-tuned through experience (Kral et al., 2016). The critical periods of early infancy, a time marked by increased plasticity, are pivotal for auditory processing and language development, as the brain's maturation and cognitive functioning are significantly shaped by varied and rich auditory experiences, which leave lasting imprints on neural pathways within this specific timeframe (Eggermont & Ponton, 2003; Mayberry et al., 2002). Conversely, a lack of adequate auditory stimulation can lead to underdevelopment in these neural pathways. Unless hearing technology is provided within the early stages of life, most children with congenital hearing loss will not have the opportunity to access speech fully, which is crucial during the foundational period for language learning (Fitzpatrick, 2015). Fortunately, some interventions can provide sensory input to a system that is structurally ready to process auditory information, even if it has never been used for hearing before (Gilley et al., 2008; Hartmann et al., 1997; Raggio & Schreiner, 1999). Despite the presence of congenital deafness, the preservation of the subcortical

auditory system (Ahmed et al., 2018; Huang et al., 2002; Striem-Amit et al., 2016), which may not be well-preserved as well (McBride et al., 2013; Tong et al., 2015), often enables individuals to perceive sound through direct stimulation of the auditory nerve also known as *cochlear*, enabling the brain to perceive sound (Kral & Sharma, 2012). Cochlear stimulation is facilitated through medical devices called cochlear implants. When auditory input is restored later in life, some aspects of the neural organization that develop normally may be irretrievably lost, rendering the necessary resources for auditory processing inaccessible (Sharma et al., 2002). At this point, early intervention of cochlear implantation is highly critical to restoring hearing to normal levels (Schauwers et al., 2004), and it brings better outcomes (Anderson et al., 2004; Edwards et al., 2006; Govaerts et al., 2002; Quittner et al., 2004; Truy et al., 1998; Yoshinaga-Itano, 2003; Zwolan et al., 2004). Loss of cochlear cells before the initiation of auditory function can potentially lead to the demise of subsequent auditory neurons in the brainstem (McBride et al., 2013; Tong et al., 2015). Hence, the timing of cochlear impairments during fetal development could significantly impact the functional integrity of auditory pathways, and consequently, affect higher-order brain systems and functions that depend on this sensory input (Kral et al., 2016; Sharma et al., 2002).

Early cochlear implantation has potential to reinstate the sense of hearing (Lima et al., 2023; Niparko, 2010), thus, congenital deafness does not anymore lead to abnormal hearing or abnormal speech development, and this early intervention leads to typical development in speech and language skills and allows for seamless integration into standard educational settings (Fulcher et al., 2012; Govaerts et al., 2002; Leigh et al., 2013; Schauwers et al., 2004; Sharma et al., 2002) with the characteristics and quality of the intervention, the level of support from the family, the timeliness of intervention, and the effectiveness of hearing aid fitting, comorbidity, as well as the degree of hearing impairment (Bubbico et al., 2007; Chiossi & Hyppolito, 2017; Dieleman et al., 2019; Schauwers et al., 2004; Sharma et al.,

2002; Vohr et al., 2008). Sensory impairments result in neurocognitive impairments (Conway et al., 2009; Kronenberger et al., 2013; Kral et al., 2016) that are still present in cochlear-implanted children even though they can develop auditory and linguistic skills and learn alongside their healthy peers (see systematic review of Lima and colleagues, 2023). In contrast, there are still significant variations in individual language outcomes among children who have a cochlear implant (Dieleman et al., 2019). Prelingually deaf children often show remarkable success in learning spoken language when they receive a cochlear implant early in childhood, particularly when they are immersed in rich language environments and receive strong support from dedicated parents and caregivers (Svirsky et al., 2004; Robbins et al., 2004), and in auditory, cortical, and social abilities as well (Sharma et al., 2002). However, those who receive cochlear implants later in life can perceive auditory stimuli, yet they often struggle to accurately distinguish complex sounds in everyday situations even after many years of using the implant (Kral & O'Donoghue, 2010; Kral & Sharma, 2012).

5. Preterm Birth

As mentioned earlier, the ontogenesis of the human auditory system represents a paradigm of intricate biological and neurological orchestration, initiating substantially before an individual's birth. This sophisticated developmental trajectory originates within the womb's protective confines, laying the foundational framework for sound perception and interpretation. The gestational maturation of the auditory system holds substantial implications for our comprehension of language acquisition, sensory processing, and cognitive development. The criticality of this developmental journey is further underscored when examining the challenges encountered by preterm infants, whose premature entry into the external environment disrupts the natural progression of sensory system maturation. This chapter aims to delve into the intricate process of auditory development from its inception during gestation, emphasizing key developmental milestones and the potential ramifications of premature birth on this vital aspect of human development especially for processing language.

5.1 Preterm Birth and Neonatal Intensive Care Unit

In typical development, a fetus is exposed to various sensory stimulations that aid in the development of body organs and the neural system, resulting in neuronal migration and maturation, dendritic growth, synapse formation, and the establishment of neural networks. This process, known as probabilistic epigenesis, plays a key role in the organization and development of different systems (Gottlieb, 2007). Premature birth disrupts these natural developmental processes that are marked by varying speeds of growth and distinct connections between skills (Sansavini et al., 2013), which may lead to development delays in language skills, sensory integration, motor delays, overall cognitive impairment, visual perception issues, deficits in executive functioning, learning challenges (Delobel-Ayoub et al.,

2009; Johnson & Marlow, 2016), and behavioral and attention difficulties (Linsell et al., 2016; Wilson-Ching et al., 2013). Cognitive development compels the brain and body of the preterm infant to adjust to an artificial setting, such as the neonatal intensive care unit (NICU). This crucial developmental phase, where they would normally be exposed to sounds in the womb, is marked by their deprivation of these intrauterine auditory experiences that may significantly impact the maturation of the auditory brain and consequently affect the development of speech and language (McMahon et al., 2012). While preterm babies in the NICU lack exposure to maternal sounds, they are not completely deprived of auditory experiences, as the type of sound stimulation they receive is influenced by the unique environment of their specific NICU, contrasting with the uniform auditory environment experienced in the womb (Vandormael et al., 2019). In this exceptional environment, the newborn experiences both under-stimulation (due to the absence of prenatal rhythmic and kinesthetic stimulations, continuous maternal contact, and restrictions imposed by the incubator and medical care) and over-stimulation due to the high-frequency noises typical of the machines and other equipment used at the NICU (Als et al., 2004; Anand & Scalzo, 2000). Nevertheless, infants who stay in a developmental care unit with high-quality standards, characterized by more effective infant pain management, enhanced regulation of external stimuli, and increased parental involvement, exhibit superior receptive language skills compared to those in units with lower-quality care (Montirosso et al., 2016). Moreover, even though the vast majority of studies emphasize on negative outcomes of premature birth, several studies showed that preterm infants may not be delayed in certain discrimination tasks (Mahmoudzadeh et al., 2013; Nishida et al., 2008; Peña et al., 2014; Saito et al., 2009). Yet, the specific short- and long-term adverse effects of hospital stimuli on infants, the optimal amount and type of auditory stimulation for language and social development, are still not clear (Philbin, 2017).

5.2 Language Development in Preterm Infants

Before the development of language understanding and speech, the auditory system begins its formation, starting early in the gestational period. By the 23rd to 25th weeks of pregnancy, crucial parts of the auditory system, like the cochlea, are already established. Post the 26th week of gestation, the cochlea's hair cells start to specialize for particular frequency ranges, transforming sound waves into electrical signals. These signals are then transmitted to the brain's auditory cortex via the auditory nerve. Consequently, from the 26th to the 30th week, the fetus becomes capable of perceiving and responding to auditory stimuli (Hepper & Shahidullah, 1994; Gagnon et al., 1987). The frequencies detected in the womb are arranged tonotopically, mirroring the distribution on the cochlea's basilar membrane. This makes the uterus an ideal environment for the maturation of the auditory system, as it serves as a low-pass filter. This filtering shields the developing hair cells from potentially damaging high-pitched sounds. Concurrently, the high-frequency areas on the membrane develop, enabling the fetus to perceive aspects of human speech like intonation, pitch, and intensity. The ability to perceive these higher frequencies (above 2kHz) is crucial for later language processing. Finally, by the 30th week of gestation, the auditory system has matured enough to discern complex sounds and differentiate various phonemes in speech (McMahon et al., 2012). The progression of language abilities in the human brain is a nuanced and dynamic process, which involves a pivotal transition from rapid developmental phases to a period of maturation. As elucidated by Scheinost et al. (2021), this transition becomes notably evident after the 30th week of gestation. It is during this phase that the functional connectivity between key language areas, specifically Broca's and Wernicke's areas, starts to intensify, signaling a shift from rapid growth to more refined maturation of these regions. However, the evolution of language skills extends beyond the maturation of these specific areas. Déak (2014) highlights the integral role of fundamental cognitive functions, including memory,

processing speed, and attention, in the development of language. These cognitive processes are crucial for the efficient acquisition and utilization of language skills. Therefore, the maturation of the brain as a whole plays a more significant role in language development than the isolated development of language-specific areas. This comprehensive maturation phase reflects a broader slowdown in developmental pace, paving the way for a more integrated and sophisticated neural functioning that underpins language abilities. For these reasons, it is not possible to consider only auditory systems' development for language abilities in infants. Moving on, gestational age serves as a robust predictor of future neurodevelopmental outcomes in very preterm infants compared to their birth weight (Woodward et al., 2006). It is crucial to emphasize the role of gestational age in forecasting future language development among premature infants, as there exists a distinct and direct correlation between the age of gestation at birth and subsequent language abilities (Foster-Cohen et al., 2007).

Preterm-born children use fewer bound morphemes, fewer irregular and over-regularized forms, and shorter utterances; they have lower vocabulary sizes, lower syntactic development, and are less likely to combine words and decontextualized word use (Foster-Cohen et al., 2007). They are at risk of linguistic disorders in their first years of life, slower than full-term children in language acquisition (Capobianco & Cerniglia 2017), and presenting social communication problems (Barre et al., 2011; Carter & Msall, 2017). Preterm children perform worse than full-term born children in both simple and complex language functions (van Noort-van der Spek et al., 2012). For detailed language impairments in preterm infants, the reader is referred to the longitudinal study of Foster-Cohen and colleagues in 2007, the meta-analysis study by van Noort-van der Spek and colleagues in 2012, and to get a broader understanding of early and long-term outcomes of infants born preterm, review of Johnson & Marlow in 2016.

6. The Current Study

In light of the above, it is sought to investigate how deaf and normal hearing infants perceive their native language and an unfamiliar language, and whether they can discriminate between them – a task that typically developing infants succeed on already at birth. It is hypothesized that there would be significant differences in cortical activation patterns, as measured by fNIRS, among healthy infants, and deaf infants when exposed to forward Italian speech and forward English speech. These differences will reflect variations in speech perception abilities and compensatory neural mechanisms. Given the onset of auditory function in utero, preterm-born infants were involved in two experimental groups based on their hearing capacities: 'normal hearing' and 'deaf.' Despite their premature birth, preterm infants possess early hearing abilities, although these may manifest differently compared to full-term infants. This classification allows for a detailed exploration of auditory processing during early developmental stages. Specifically, it is hypothesized that deaf infants will show different patterns of brain activation compared to healthy infants, indicating altered neural pathways for processing speech due to their developmental and sensory differences. Healthy infants are expected to exhibit left-temporal brain activation in response to forward Italian speech, more right-temporal activation in response to forward English speech as a rhythmically different language, and bilateral-temporal areas activation when exposed to non-linguistic stimuli (backward speech). Deaf infants are expected to exhibit reduced or different patterns of activation in the traditional language areas due to their auditory deprivation, potentially showing greater activation in visual or somatosensory cortices as a compensatory mechanism.

6.1 Methods

6.1.1 Participants

Data from a total of 19 infants (aged from *9* to *266* days postnatal, *M = 131 days*) were included in the experiments. A group of infants with congenital moderate-to-severe deafness (full-term *N = 5*, testing age *M = 124* days; prematurity *N = 2* of which 1 extremely, 1 moderately preterm-born, postnatal testing age *M = 100*), and a control group with normal hearing (full-term N = 10, M = 136; prematurity N = 2 of which 1 very, 1 moderately preterm-born, postnatal testing age M = 130) with APGAR score of 7+ at birth, and 8+ 5 minutes after birth were tested. According to parental report, all infants were exposed to Italian 100% of the time in utero and had no exposure to English. An additional 48 infants were tested but were excluded from analysis due to fussiness, unilateral hearing loss, insufficient data, machine/computer errors, or exposure to languages other than Italian prenatally.

The data was collected by Gaia Lucarini and Caroline Nallet (DPSS) as part of a larger study investigating basic speech perception abilities in deaf and cochlear-implanted infants.

6.1.2 Design and Stimuli

A female native speaker of each language (Italian, English) for a total of 4 conditions that are Italian-Forward (ITFwd), Italian-Backward (ITBwd), English-Forward (ENGFwd), and English-Backward (ENGBwd) was recorded reading aloud from the children's book *The Paper Bag Princess and The Three Wishes.* Backward speech, created using the software Praat, for both Italian and English is considered a non-linguistic control that matches forward speech in both intensity and pitch but is distinctly non-linguistic, as humans are unable to produce backward speech (Gervain et al., 2011; Peña et al., 2003) which contains sounds that

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cannot be produced by the human vocal tract (May et al., 2017) and it is in general unintelligible. The sentences in each of the four conditions were presented in a simple block design (Fig. 1*B)*, with the order of blocks pseudorandomized and counterbalanced across subjects. The sentences in the two languages and the two orders of presentation (forward and backward) have been matched in intensity and duration. The study was divided into 2 halves (Fig. 1*A*), each composed of 24 blocks for each condition such that even if infants fussed out before reaching the end of the study, they would provide data in each condition.

Figure 1

Study Design
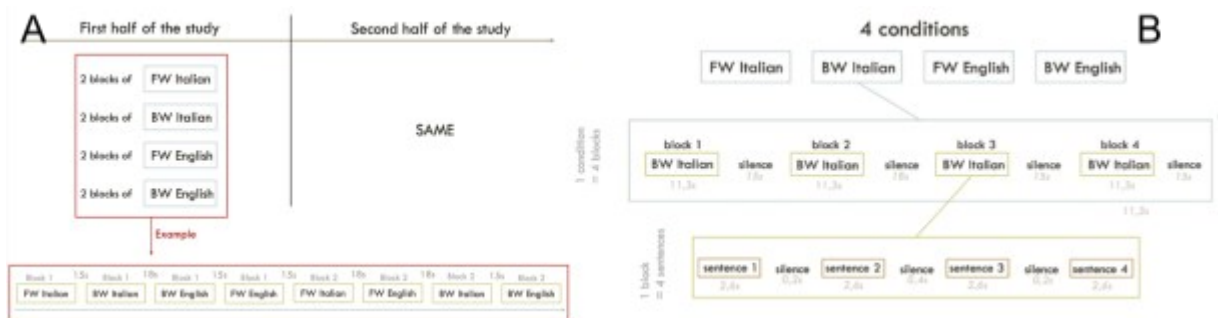
Note. (A) Blocks also were spaced at time intervals of varying duration (15s-18s) to avoid inducing phase-locked brain responses. The 16 blocks were presented in an interleaved fashion in such a way as to disallow more than two consecutive blocks of the same type. The order of the blocks was pseudorandomized and counterbalanced across subjects. (B) Within blocks, sentences were separated by pauses of varying length (0.2-sec.–0.4-sec.), yielding blocks of about 2.6-sec.

6.1.3 Procedure

A NIRSport2 fNIRS machine with a source-detector separation of 3 cm and two continuous wavelengths of 695 and 830 nm was used, with a sampling rate of 20.345hz. A stretchy cap with embedded optical sensors was positioned on the infants' heads using surface landmarks (Fig. 2), specifically the nasion and preauricular points, with a focus on targeting the language-related areas within the bilateral temporal, frontal, and parietal areas. These regions constitute the language network (Dehaene-Lambertz et al., 2002; Dehaene-Lambertz et al.,

2006; Frederici, 2002; Frederici et al., 2006; Gervain et al., 2008). The playback and control of the stimuli were managed by a Dell laptop computer, which also operated the NIRS machine. Infants were tested in a silent, sound attenuated room at the University of Padua Hospital, and in BabyLab at the University of Padua. Younger infants were asleep during the study, while older infants were seated on their parent's lap and exposed to muted cartoon series on a screen positioned around 80 cm from the infants (Fig. 3) using E-Prime software.

Figure 2 and Figure 3

Infants wearing a stretchy head cap of NIRSport2 and sitting on their parent's lap


Note. Infants were tested while watching muted cartoon series and hearing speech conditions. The pictures are taken before and during testing at BabyLab at the University of Padova.

The optical probe was placed on the infant's head, as shown in Fig. 4. In cases where infants lost attention, a researcher positioned discreetly behind the computer screen introduced quiet toys to re-engage their attention. This standardized procedure was consistently followed across all study groups.

Figure 4

Cortical Regions
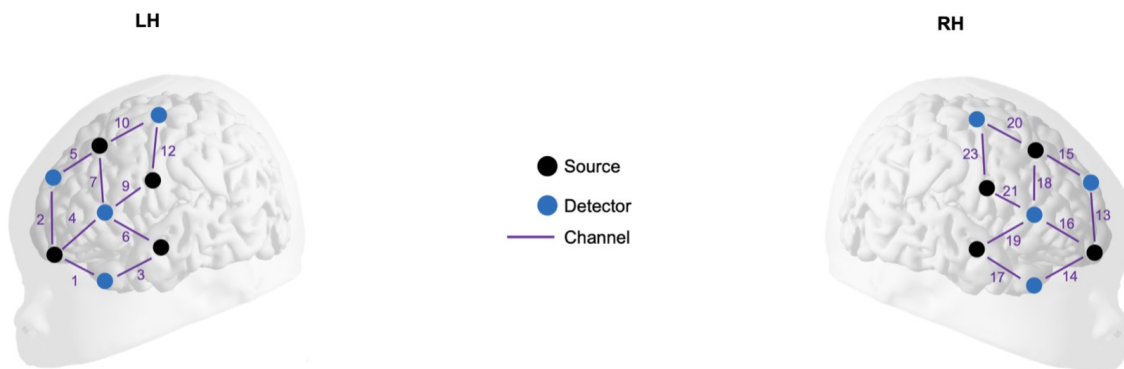
Note. The cortical regions underlying NIRS channels overlaid on a schematic infant brain. Although individual variation cannot be excluded, this placement ensured recording from frontal, frontotemporal, and frontoparietal brain regions. The locations were projected down onto the cortical surface to identify the regions underlying the NIRS channels for each infant. A channel was then labeled according to the localization found in the majority of participants. Accordingly, channels 1, 2, 4, 5 in the left hemisphere (LH), and 13, 14, 15, and 16 in the right hemisphere (RH) query the frontal lobe, channels 3 in the LH and 17 in the RH are positioned over the temporal lobe, channels 10, 12 in the LH and 20, 23 in the RH are parietal, whereas channels 6, 7, 9, 18, 19, and 21 span two lobes.

6.1.4 NIRS Data Analysis and Statistics

The NIRS machine measured the intensity of the transmitted light, from which concentration changes of oxygenated hemoglobin (OxyHb) and deoxygenated hemoglobin (DeoxyHb) were calculated using the modified Beer-Lambert Law. To eliminate noise (e.g., heartbeat) and overall trends, the data were band pass-filtered between 0.01–0.7 Hz. Movement artifacts, defined as concentration changes above 0.1 mmol*mm over 0.2 sec were removed by rejecting block-channel pairs in which artifacts occurred. For the valid non-rejected blocks, a baseline was linearly fitted between the means of the 5 sec preceding the onset of the block and the 5 sec starting approximately 21 sec after the onset of the block. Following bandpass filtering and artifact removal, the mean concentrations of oxyHb and deoxyHb across all blocks for each condition within the 21-second stimulation period (11-second stimulation + 10-second return to baseline relaxation period) were computed. The 20 channels based on

hemisphere (LH vs. RH) and region of interest (ROI; Temporal vs. Parietal regions), comparing activations for the four conditions within these broadly defined brain areas were categorized. Thus, the left temporal ROI encompassed channels 3 and 6, the right temporal ROI channels 17 and 19, the left parietal ROI channels 9 and 12, and the right parietal ROI channels 21 and 23.

To compare how infants process the different conditions, an analysis of variance test (ANOVA) of the within-subject factors Condition (ITFwd/ITBwd/ENGFwd/ENGBwd), Hemisphere (LH/RH), and Region of Interest (Temporal/Parietal), and the between-subject factor Group (Normal-hearing/Deaf) over OxyHb and DeoxyHb was conducted, separately.

Given that it is inconclusive in the literature how the etiology of deafness may impact language development and because our sample was relatively small, the etiology of hearing impairment in the statistical testing of the current study was not considered.

6.2 Results

The resulting grand averages of the two groups, deaf and normal-hearing infants, are sequentially shown in Fig. 5 and Fig. 6.

The data analysis concentrated on the variable of OxyHb due to its established significance as the most robust indicator of neural activity in infants, as highlighted in studies by Aslin (2013), Gervain et al. (2011), and Lloyd-Fox et al. (2010). The ANOVA with the within-subject factors Condition (ITFwd/ITBwd/ENGFwd/ENGBwd) x Hemisphere (LH/RH) x Region of Interest (Temporal/Parietal), and the between-subject factor Group (Normal-hearing/Deaf) over OxyHb yielded a significant interaction between Condition and Group [F (2, 43) = 3.007; P = 0.048] due to a large negative, i.e. inverted response in the deaf

group to ENGFwd, and a large positive, i.e. canonical response to ITABwd in the normal hearing group. No other statistically significant results were found.

A similar ANOVA utilizing the factors Speech (ITFwd/ITBwd/ENGFwd/ENGBwd) x Hemisphere (LH/RH) x ROI (Temporal/Parietal) over deoxyHb concentrations found a statistically significant [$F = (3, 46) = 3.004$; $P = 0.045$] due to greater activation in the control group over the right parietal area for ENGBwd speech than in the experimental group. No other significant results have been found for DeoxyHb.
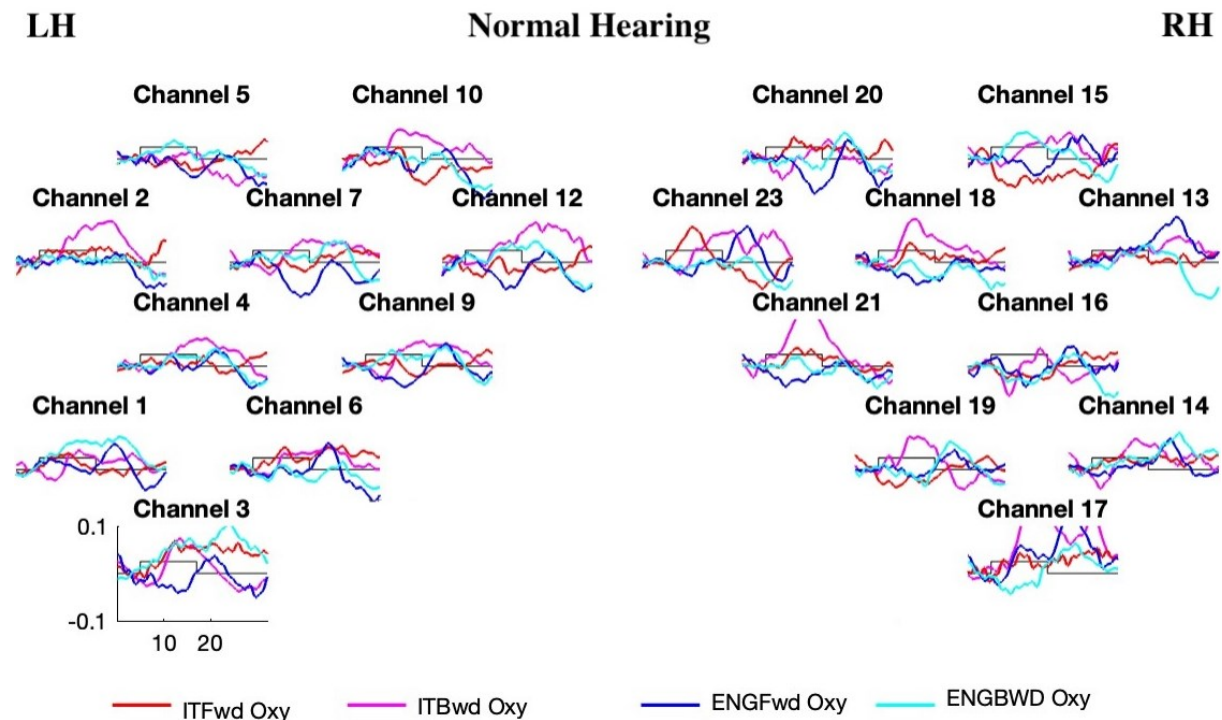
Figure 5

Grand Average of Oxygenated Hemoglobin Changes in the Experiment Group
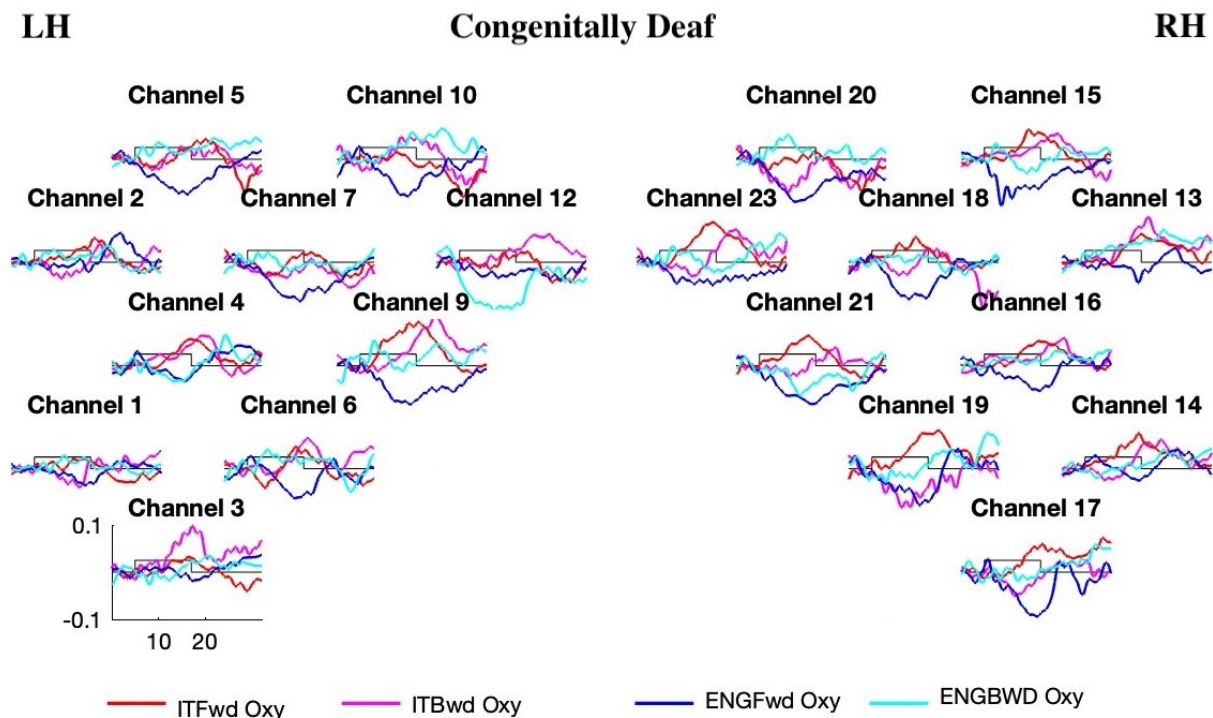
Note. The grand average results of oxygenated hemoglobin for the congenitally deaf group in response speech and non-linguistic speech stimuli. Channels are plotted following the same placement as in Fig. 4. The x-axis depicts time measured in seconds, while the y-axis displays concentration measured in mmol-mm. A rectangular segment along the horizontal axis denotes the duration of stimulation. The solid red lines on the graphs illustrate the levels of oxyHb concentration in reaction to the Italian-Forward speech, pink lines to the Italian-Backward speech, blue lines to the English-Forward speech, and turquoise to the English-Backward speech.

Figure 6

Grand Average of Oxygenated Hemoglobin Changes in the Control Group

Note. The grand average results of oxygenated hemoglobin for the normal hearing group in response to speech and non-linguistic speech stimuli. See the explanations in Fig. 5.

6.3 Discussion

This study aimed to investigate the neural correlates of the perception and discrimination of the native language and a rhythmically different unfamiliar language in deaf and normal-hearing infants. Using functional near-infrared spectroscopy (fNIRS), it was hypothesized that there exist significant differences in cortical activation patterns between among healthy and deaf infants exposed to forward and Italian and English speech stimuli. Our findings offer insights into early language perception and the impact of auditory deprivation on neural processing mechanisms during infancy. No significantly greater response has been found to ITFwd speech in the healthy group than in the deaf group, as hypothesized. In contrast, consistent with the hypothesis, significant differences in cortical activation patterns between deaf and normal-hearing infants were observed.

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Notably, the deaf infants exhibited a distinct pattern of brain activation characterized by a large negative response to ENGFwd speech and a large positive response to ITBwd speech. This inverted response in the deaf group, different from the response patterns of the typical group has two implications. First, it shows discrimination between some of the language conditions, suggesting that deaf infants have more residual perceptual sensitivities than previously believed.

Second, these results suggest altered neural processing mechanisms in response to linguistic stimuli due to auditory deprivation, and hemispheric interaction could be lower as decreased RH activity is seen when a rhythmically different language is perceived than in normal-hearing peers.

Our findings support the notion that auditory deprivation in deaf infants leads to adaptive changes in cortical organization and speech-processing pathways. The different patterns of activation observed in traditional language areas among deaf infants may indicate a reorganization of neural networks to accommodate alternative sensory modalities, such as visual or somatosensory inputs, as compensatory mechanisms for language processing. By elucidating the differences in neural processing mechanisms between deaf and normal-hearing infants, our study provides insights into the dynamic nature of early brain development and the plasticity of the infant brain. These findings have important implications for our understanding of developmental neuroscience and the plasticity of the infant brain, highlight the dynamic nature of neural development, and underscore the importance of early intervention strategies for infants with hearing impairments to optimize language acquisition and cognitive development. Therefore, early implantation during a critical sensitive period not only promotes more effective cortical maturation and speech perception development (Kral & Sharma, 2012; Ponton et al., 1996) but it is also recommended for optimal language development to undergo cochlear implantation even before 9 months of age (Dettman et al.,

2021). Deaf children may present lower scores in many cognitive domains which are correlated with hearing and language outcomes despite early technological aids compared to normal hearing peers (Lima et al., 2023). However, they can develop auditory and linguistic skills and learn alongside their typically developing peers by combining electronic auditory devices with a suitable period of speech-language-hearing rehabilitation (Bubbico et al., 2007; Sharma et al., 2002).

6.3.1 Limitations and Future Directions

Our study has promising results, as both differences between groups were identified and deaf babies show different responses to the different conditions. This study, while contributing significant insights into early language perception in infants, is subject to certain limitations that warrant careful consideration. Firstly, the sample size employed in our investigation was relatively modest, which may constrain the extent to which our findings can be extrapolated to broader populations. Although there was ensured representation across both deaf and normal-hearing infants, the limited sample size compromises statistical power and increases the risk of Type I or Type II errors. Future research endeavors would benefit from expanding sample sizes to enhance the reliability and external validity of observed patterns, facilitating more definitive conclusions regarding intergroup disparities in cortical activation during language perception tasks.

Secondly and related to the previous point, the lack of classification of hearing impairment severity within the deaf group, which was due to the small sample size, may have impacted the study results by potentially overlooking important variations in auditory processing abilities among deaf infants. Different degrees or types of hearing loss could influence cortical activation patterns and language perception abilities, leading to variability within the deaf population. Without accounting for these variations, the study may have failed to capture

the full spectrum of responses to linguistic stimuli among deaf infants, limiting the generalizability of the findings and the ability to tailor interventions effectively. Future research could address this limitation by categorizing deaf infants based on the severity or type of hearing impairment. This classification approach may provide deeper insights into the variability observed within the deaf population and inform tailored interventions for optimizing language development in this diverse group.

Thirdly, infancy is characterized by rapid neurodevelopmental changes, with the developing brain displaying varying patterns of cortical activation in response to linguistic stimuli at different developmental stages. By including participants ranging from neonates to older infants, our study inadvertently introduces developmental heterogeneity, potentially obscuring subtle group distinctions. Future investigations would benefit from narrowing participant age ranges to specific developmental periods. This focused approach would allow for a more homogeneous examination of developmental trajectories and facilitate nuanced insights into language perception dynamics during critical periods of neurodevelopment.

Moreover, the inclusion of premature infants in our study, categorized based on their hearing status into the deaf and normal hearing groups respectively, introduces another potential limitation. While this classification facilitated the examination of auditory processing during early developmental stages, it may have inadvertently introduced confounding variables related to prematurity. Premature infants often experience unique developmental trajectories and neurological vulnerabilities compared to full-term infants, which could influence their neural responses to linguistic stimuli independently of their hearing status. Therefore, the differences in cortical activation patterns between premature and full-term infants warrant caution, as these differences may reflect not only the effects of hearing impairment but also the effects of prematurity. Importantly, however, as preterm birth is a common cause of hearing loss, these factors cannot fully be separated in clinical practice. Furthermore, the

involvement of premature infants in our study offers valuable insights into the longitudinal trajectory of language development in this population. As indicated by previous research (Capobianco & Cerniglia, 2017), premature infants typically regain fundamental developmental milestones, including language skills, during later infancy. Therefore, a longitudinal study tracking the language development of premature infants exposed to linguistic stimuli could provide valuable information regarding the efficacy of early intervention strategies and the extent to which cortical activation patterns predict language outcomes over time. A possible improvement in future research endeavors could involve directly comparing premature infants with their full-term peers within each hearing group as well. This comparative approach would enable a more nuanced understanding of the specific effects of prematurity on language perception and cortical activation patterns, independent of hearing status. By disentangling the contributions of prematurity and hearing impairment, researchers can elucidate the unique challenges faced by premature infants in language development and inform targeted intervention strategies to support their linguistic outcomes.

7. Conclusion

This study provides instructive insights into the cortical activation patterns associated with speech perception in deaf and normal-hearing infants during early developmental stages using functional near-infrared spectroscopy (fNIRS). Findings revealed significant differences in cortical activation patterns between deaf and normal-hearing infants when exposed to a rhythmically different unfamiliar language -ENGFwd and non-speech stimuli -ITABwd. Deaf infants exhibited distinct patterns of brain activation characterized by an inverted response to ENGFwd and a canonical response to ITABwd speech, suggesting compensatory neural mechanisms in response to auditory deprivation. Additionally, the inclusion of premature infants underscores the importance of considering developmental trajectories in language acquisition. Future longitudinal studies could provide further insights into the efficacy of early interventions. Overall, these findings highlight the dynamic nature of early brain development and underscore the importance of tailored interventions for optimizing language acquisition, particularly in vulnerable populations. By elucidating the neural mechanisms underlying language perception in infancy, it is possible to inform evidence-based interventions aimed at promoting cognitive development and linguistic outcomes in early childhood.

8. References

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