Université de Mons
Faculté de Psychologie et Sciences de l'Education

Speech sound processing by children with cochlear implants: what impact on linguistic development? Analysis of acoustic production profiles and their relation to phonological and morphosyntactic components.

Sophie Fagniart

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Jury

Prof. Crouzet Olivier, Université de Nantes
Prof. Huet Kathy (Directrice), UMONS
Prof. Grandon Bénédicte, Université de Nantes
Prof. Lahaye Willy, UMONS
Prof. Leybaert Jacqueline, Université Libre de Bruxelles
Prof. Piccaluga Myriam (Co-directrice), UMONS
Prof. Rinaldi Romina, UMONS

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Abstract

The doctoral thesis investigates the phonetic and linguistic skills of groups of children with cochlear implants (CIs) and children with typical hearing to explore the links between the perceptual limitations of CIs and language skills. At the phonetic level, various phonetic segments are compared, whose acoustic correlates reflect contrasting difficulties related to sound coding by CIs: nasal and oral vowels (related to low-frequency information), fricative consonants (related to high-frequency information), and voiced and voiceless stop consonants (where the distinction relies on temporal cues that are expected to be better coded by CIs). The results highlight a specific impact of the perceptual limitations of CIs on the productive skills involving vocalic nasality and fricatives, as well as specificities in the phonetic implementation of the voiced/voiceless stop consonant distinction. However, compensation strategies are observed among groups of children who are exposed early and intensively to Cued Speech, demonstrating the value of multimodal speech activation in their management. Positive effects of early implantation are also found. The study of lexical and grammatical skills shows specific difficulties in processing grammatical and lexical morphemes whose morphophonological alternations are carried by nasal and oral vowels, as well as narrative production skills characterized by lower Mean Length of Utterances and fewer occurrences of function words and complex verbal forms. Lexical diversity is also lower in the CI group. A specific link between phonological and grammatical skills is observed in the CI group, revealing a strong interdependence that is discussed in connection with phonological theories of morphosyntactic difficulties. Finally, phonological, lexical, and grammatical skills are linked to acoustic production profiles through factor analyses and hierarchical ascending analyses, which identify different profiles among the children: some with very low performances and others with performances approaching those of their peers with typical hearing of the same auditory age. A one-year follow-up conducted on a subgroup of children, however, reveals a stagnation in performance among the majority of retested children, suggesting slower developmental profiles probably due to the limitations related to perceptual processing.

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List of Abbreviations

AA = auditory age
aD = ampDiff
CA = chronological age
CI(s) = cochlear implant(s)
CS = Cued Speech
E.D. = Euclidean distance
F1 = first formant
F2 = second formant
F3 = third formant
HAC = hierarchical agglomerative clustering
lD = levelD
MS = morphosyntax/morphosyntactic
NAF = Nasalization from Acoustic Features
PCA = Principal components analysis
SES = socioeconomic status
SWPM = sentence/word picture-matching
TH = typical hearing
VOT = voice onset time
VP = velopharyngeal

Chapter 1 General introduction

Deafness is among the most prevalent sensory impairments in children, affecting approximately 34 million worldwide (World Health Organization, 2024). The impact of deafness on the development of oral language in cases of moderate to severe or profound deafness is significant, often leading to delayed and/or atypical development. Sign languages have been developed to establish a gestural communication mode without relying on spoken language. Conventional hearing aids, which can compensate for moderate hearing loss, are insufficient in more severe cases to achieve a level of auditory acuity that allows adequate perception of spoken language (Leybaert & Colin, 2007).

In this context, the introduction of the cochlear implant, a device that restores some of the auditory function lost due to inner ear impairment, has led to a revolution in audiology: it has become possible to provide auditory input directly within the inner ear, thus offering crucial assistance for severe to profound sensory hearing loss in both children and adults. The benefits of cochlear implantation are well established: with appropriate follow-up and care, children and adults are capable of achieving a sufficient level of perceptual ability for effective oral communication (Tamati et al., 2022).

However, the cochlear implant does not restore a typical hearing. The device is constrained by current technological limitations and can only transmit partial acoustic information, as will be further described in Chapter 2. Therefore, it is essential to question the precision with which children can acquire all the phonological contrasts of their native language and their associated phonetic representations, and subsequently develop various linguistic competencies such as lexical and morphosyntactic skills with similar efficiency to their typically-hearing peers.

Investigating how children with prelingual deafness, who have had delayed and partial access to the acoustic information of their auditory environment, develop their language skills is of great interest. Indeed, most theories on language acquisition mechanisms agree on the necessity of rich, complete, varied, and, above all, early language input for harmonious linguistic development. How do these same mechanisms operate in children with cochlear implants? Can intrauterine and early postnatal auditory deprivation be compensated for after the implantation? Moreover, if the implant provides only partial access to acoustic information, what about the perception of phonological contrasts and prosodic variations which in the child's native language typically rely on this missing or degraded information? Children with cochlear implants may have difficulties perceiving and processing the speech signal as precisely as those with normal hearing. What about the acquisition of so-called *higher-level* language skills, such as lexical and morphosyntactic skills, in the context of perceptual limitations in *lower-level* aspects related to speech sound perception? Can relationships be established between initial perceptual deficits and the level of development of language skills such as morphosyntax? These are some of the questions that this doctoral thesis will attempt to answer.

By deepening our understanding of the language development of deaf children with cochlear implants, we aim to better comprehend the general mechanisms of native language acquisition, particularly the impact of potentially degraded linguistic input on various language skills, as well as the interactions that these skills may have with each other.

In this context, the present thesis aims to study how deaf children with cochlear implants develop various components of language compared to hearing children. This investigation will take the form of experimental articles addressing specific aspects related to our research questions. This introductory chapter will briefly present the central theoretical concepts related to deafness, the different types and their etiologies, and the possibilities for remediation, as well as the functioning of cochlear implants and the different modes of communication available to deaf individuals. The main research questions of the thesis will be outlined, and a brief overview of the experimental studies conducted to investigate the language skills of deaf children will also be presented. The following chapters will each focus on a specific experimental study targeting particular aspects of language ability and the associated research questions, with a dedicated theoretical introduction providing the relevant context.

1. Theoretical background

1.1. Deafness: Definition, Etiology, and Diagnosis

The term *deafness* refers to the reduction of hearing acuity, encompassing various levels, types, and etiologies of hearing loss. This section will clarify the different types of deafness, their characteristics, and etiologies before addressing the various remediations that can be offered for hearing impairments.

The auditory system can be divided into three parts: the outer (or external) ear, consisting of the auricle and external auditory canal; the middle ear, consisting of the tympanic membrane, tympanic cavity, ossicular chain, Eustachian tube, and middle ear muscles; and finally, the inner ear, which consists of the membranous labyrinth, including the vestibule and cochlea (see Figure 1.1).

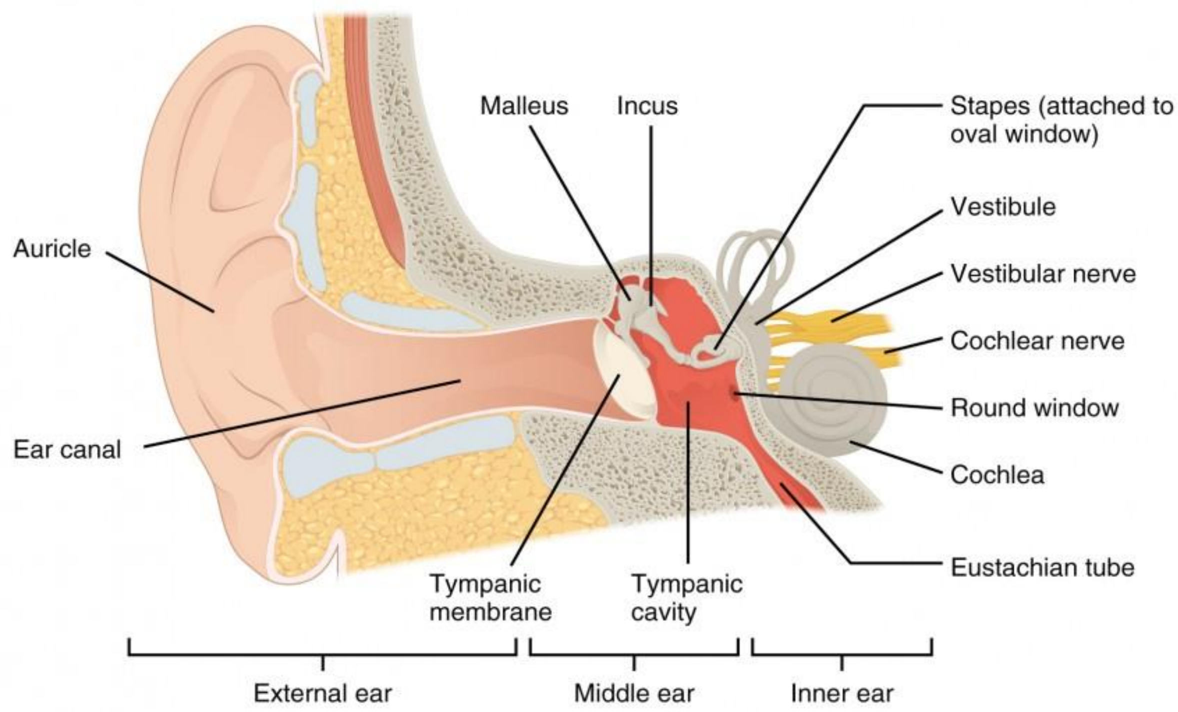

Figure 1.1: Anatomy of the peripheral auditory system. From (Kelly, s. d.), figure 8.5

The sound signal, a mechanical wave caused by variations in air pressure, is captured by the auricle of the ear and directed from the external auditory canal to the tympanic membrane. The tympanic membrane, a flexible membrane at the entrance to the middle ear, vibrates, triggering the movement of the ossicles, first the malleus, then the incus, and finally the stapes. The movements of the ossicular chain mechanically amplify sound vibrations. The stapes, by its back-and-forth motion, exerts pressure on the oval window, the interface between the middle and inner ear, and thus transmits the sound vibration to the inner ear, which primarily contains a liquid medium. The mechanical energy transmitted by the ossicular chain transforms into vibrations within the liquid medium of the cochlea. The sound vibrations set the cochlear fluids in motion and move a membrane in its center, the basilar membrane, on which the organ of Corti is located.

The organ of Corti contains the sensory cells, called hair cells, responsible for mechano-electrical transduction, meaning the transformation of the mechanical vibration caused by the sound stimulation into variations of electrical energy interpretable by the brain. The cochlea transmits sound information tonotopically, meaning that each sound frequency is transmitted to a specific location on the basilar membrane. This tonotopic organization is linked to the biomechanical properties of the basilar membrane: it is flexible and narrow at its base, favoring the vibration of high-frequency sounds, and wide and rigid at its apex, favoring the amplification of low-frequency sounds. This mechanism is responsible for the discrimination of sound frequency (see Figure 1.2).

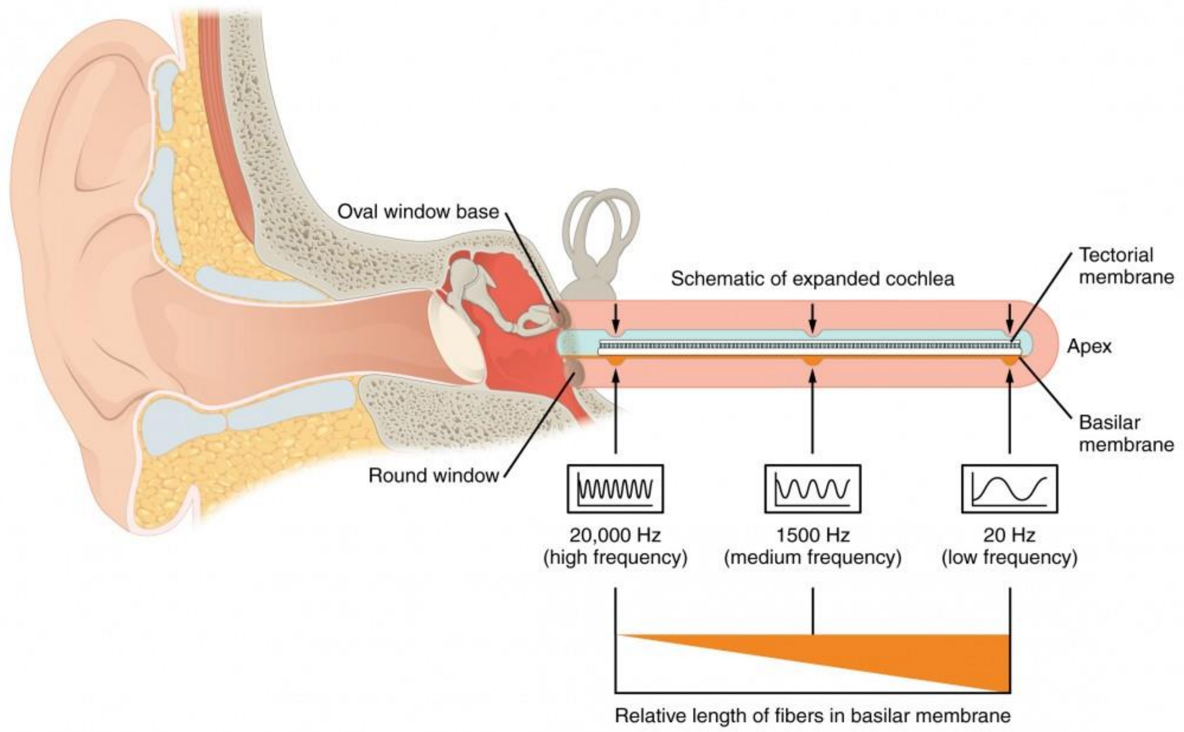

Figure 1.2: Illustration of the cochlear tonotopy. From Kelly (s. d.), figure 8.10

It should be noted that the frequency ranges represented within the membrane determine the human auditory field and that the distribution of these frequency zones is not linear: the distance between two zones on the membrane does not correspond to a fixed gap between two frequencies processed by these zones. Thus, the human auditory field ranges from 20 to 20,000 Hz, and the sounds commonly used by humans (speech sounds) are located at frequencies more widely represented on the basilar membrane, particularly from 125 to 8,000 Hz.

The mechanisms causing deafness can be related to incomplete transmission of sound to the cochlea, resulting in what is known as *conductive* deafness, or due to damage to the inner ear and, therefore, to the coding of sound, resulting in what is known as *sensorineural* deafness.

Conductive deafness can occur due to damage to the outer ear, hindering sound passage through the auditory canal. These outer ear pathologies are usually benign (presence of earwax plugs or foreign objects, external ear infections) but can also be related to congenital malformations that completely obstruct the auditory canal (atresia with stenosis of the auditory canal). Most conductive deafness is related to damage to the middle ear, known as “middle ear infections”. Otitis media is one of the most common afflictions in children. Acute otitis media, inflammation of the middle ear following bacterial penetration, with signs and symptoms of infection, is distinguished from serous otitis media, characterized by the presence of non-purulent fluid in the middle ear. The most likely etiology of serous otitis media is related to mechanical or functional dysfunction of the Eustachian tube, preventing proper ventilation of the middle ear. Middle ear infections cause conductive deafness due to reduced mobility of the ossicular chain and tympanic membrane due to fluid presence in the tympanic cavity. Prolonged and untreated acute and serous otitis media can lead to what are called *chronic* middle ear infections, which may complicate into tympanosclerosis (scarring tissue development on the tympanic membrane) or cholesteatoma (epidermal cyst development on the inner surface of the tympanic membrane), potentially leading to more lasting hearing loss. In cases of conductive deafness, hearing loss is generally between 21 and 40 dB, considered mild, but in more severe cases, moderate hearing loss with a loss of 41 to 55 dB can be observed (Dulguerov, 2005).

Sensorineural deafness is caused by damage to the inner ear, auditory pathways, or auditory nerve centers. Hearing loss is caused by a defect or inability of sensory cells to transform sound into an electrical signal (endocochlear damage) or by a defect in transmitting electrical information to the brain through the auditory pathways (retrocochlear damage). Congenital deafness is present from the child's birth, and genetic causes are distinguished from *acquired* causes. Sensorineural hearing loss of genetic origin is the most common and accounts for two-thirds of observed hearing loss cases (Lina-Granade & Truy, 2017). Ninety percent of genetic hearing loss is non-syndromic, while 10% is associated with genetic syndromes that affect other organs. Non-syndromic genetic hearing loss is linked to mutations in genes that are primarily transmitted in an autosomal recessive manner, leading to bilateral hearing loss of varying severity, but most often severe to profound (Ciardelli & Ligny, 2020). Many genetic syndromes cause sensorineural deafness, the most frequent being Pendred, Usher, Waardenburg-Klein, and Alport syndromes, which are associated with various organic impairments and different degrees of deafness. Acquired deafness in children most often results from prenatal damage to the child's inner ear, caused by infections contracted by the mother during pregnancy, the most common being cytomegalovirus infection. Perinatal deafness can occur following anoxia during childbirth (distress, respiratory insufficiency of the newborn) or extreme prematurity. Postnatal deafness in children is most often due to bacterial meningitis. Acquired deafness in adults can be of infectious origin (labyrinthitis, Lyme disease, herpes zoster, etc.), traumatic (fracture, concussion, barotrauma, noise exposure, etc.), related to inner ear conditions (Ménière's disease, acoustic neuroma, presbycusis, etc.), or related to the aging process of sensory cells (presbycusis) (Sauvaget & Tran Ba Huy, 2005).

Differential diagnosis between conductive and sensorineural deafness is made through a clinical examination, including a precise history, observation of the outer ear and tympanic membrane, and subjective (pure-tone and speech audiometry) and objective (tympanometry, evoked otoacoustic emissions, medical imaging) auditory tests. The clinical examination will aim to determine the type of deafness, its etiology, and its severity.

Deafness can be qualified in terms of severity, judged by the level of intensity (in decibels) required to perceive a sound. The severity of hearing loss can be assessed using pure-tone audiometry. In a pure-tone audiometry test, the patient is exposed to sounds of increasing (or decreasing, depending on the technique) intensity across the various frequency ranges of the auditory field (from 125 to 8,000 Hz). The patient must respond (by raising a hand, pressing a button) as soon as they perceive the sound, allowing the determination of minimal perceptual thresholds (the minimum intensity at which the patient perceives the sound) for the tested frequencies. It is then possible, for each ear, to determine an average hearing loss. Hearing thresholds are considered normal if they range between 0 and 20 dB. Deafness is considered to begin at hearing thresholds of 20 to 40 dB, classified as mild; a loss of 40 to 70 dB is considered moderate, while losses above 70 dB and 90 dB are classified as severe and profound, respectively (Bonfils & Avan, 2005). In these latter cases, speech cannot be perceived correctly without a hearing aid, while in less severe losses, speech can be perceived but inaccurately.

Deafness occurring before the age of 1 to 2 years is called *prelingual* as it occurs before the onset of the child's language learning. Between the ages of two to 3-4 years, it is classified as *perilingual*, while deafness occurring after the establishment of the child's language, around 4-5 years, is classified as *post-lingual*.

1.2. Conventional hearing aids

While the majority of conductive hearing losses can be restored through medical or surgical intervention, sensorineural hearing loss is irreversible and requires the use of hearing aids to establish a certain level of auditory acuity.

The goal of a hearing aid is to transmit sound through amplification in order to restore optimal access to oral communication (Klinck et al., 2020). Conventional hearing aids are the most common and involve removable devices that aim to amplify sound waves and transmit them to the ear via air conduction (i.e., through the transmission of sound waves by the vibration of the tympano-ossicular chain). These devices are equipped with microphones, a processor, and a speaker. The microphones capture the surrounding sounds and transmit them to the processor, which performs various operations (filtering and reducing/amplifying frequency ranges to improve the signal-to-noise ratio). The speaker then transmits the resulting sound into the external auditory canal. These devices come in the form of behind-the-ear models or in-the-ear systems. Bone-anchored hearing aids aim to transmit sound vibrations through bone conduction, using a device that is either removable or screwed into the mastoid bone. Middle ear implants may be proposed in cases of anatomical impossibility or ineffectiveness of conventional hearing aids. They are surgically placed on the tympano-ossicular system to directly amplify vibration. Finally, devices that function through electro-acoustic stimulation can be offered when conventional hearing aids are not sufficient to achieve a comfortable level of auditory acuity. This includes cochlear implants, which will be described below, and auditory brainstem implants. The latter are placed at the cochlear nucleus and are recommended in cases of auditory nerve damage.

1.3. Cochlear Implant

The first cochlear implant prototypes were tested between 1957 and the 1970s, when they began to be marketed. The first cochlear implant in a child was performed in 1990 (Tamati et al., 2022). Its use has become increasingly widespread, and the technologies it comprises are constantly improving. By 2019, approximately 736,900 people worldwide had been implanted (NIDCD, 2024). Since its introduction, the rencommendation for cochlear implants has significantly evolved to include increasingly diverse profiles, allowing for very early implantation in children with congenital hearing loss. Currently, the recommendations of the Haute Autorité de Santé suggest that cochlear implantation in children should be performed as early as possible in cases of severe to profound hearing loss where conventional hearing aids are insufficient (HAS, 2012). The French Society of Otolaryngology (SFORL) has recently recommended bilateral cochlear implantation for all children with severe to profound bilateral hearing loss (Simon et al., 2019). In Belgium, the National Institute for Health and Disability Insurance (*Institut National d'Assurance Malalide-Invalidité - INAMI*) covers the implantation of both ears in cases of severe bilateral hearing loss up to the age of 18. In cases of unilateral deafness, the implantation of the deaf ear is reimbursed up to the age of 4 for congenital deafness and up to the age of 18 for acquired deafness (Moniteur Belge, 2023).

The cochlear implant is a device consisting of external and surgically implanted internal parts. The external component includes a microphone, a processor, and an external antenna, while the internal component includes an internal antenna (the internal and external antennas are magnetically linked through the skin), a receiver-stimulator, and electrodes (placed in an electrode array). The microphone captures sound and converts acoustic information into an electronic signal (see Figure 1.3). This information is transmitted to the processor, which filters and decomposes the signal portions according to their characteristics (frequency, intensity, duration). This filtering is done to transmit the different filtered frequency bands to specific points on the cochlear membrane, recreating the tonotopic mechanism of the healthy ear.

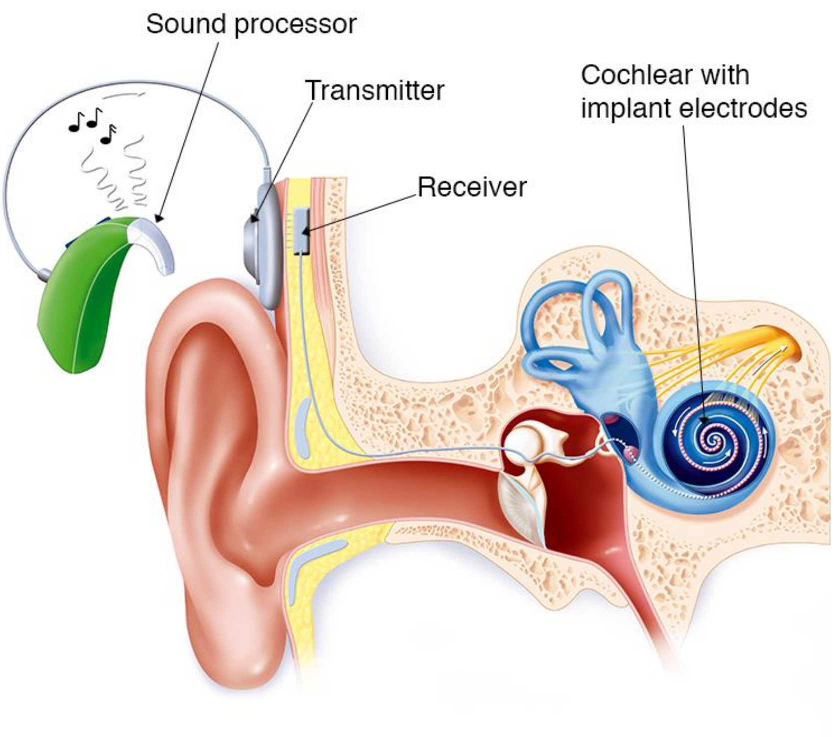

Figure 1.3: Cochlear implant functionning. From Friesen (2019)

The microphone and processor system is adjustable to regulate the device's volume and sensitivity. The decomposed signal is sent to the external antenna, which transmits it to the internal antenna and then to the receiver-stimulator, which decodes the information and stimulates the electrodes corresponding to the signal portions decomposed by the processor. The stimulation of the electrodes within the cochlea stimulates the auditory nerve fibers through electrical impulses transmitted by the electrodes. This mechanism replaces the function of deficient or absent sensory cells and preserves a certain cochlear tonotopy, allowing discrimination of sounds of different frequencies.

There are different models of implants, with the main manufacturers being MXM in France (marketing the "Digisonic" implant), Advanced Bionics Corporation ("Clarion" implant), Cochlear Corporation ("Nucleus" implant), and MedEI Corporation ("Combi 40" implant) (Grandon, 2016). Different coding systems define the types of processes involved in converting the input signal into electrical signals to be transmitted to the auditory nerve, with the aim of providing as much information as possible. The first models contrasted two types of strategies: those that prioritized spectral information (e.g., “Multi-Peak” or “Spectral Peak” strategies) and those that prioritized temporal information (e.g., “Simultaneous Analog Stimulation”, “Continuous Interleaved Sampling” or “Multi-Pulse Stimulation”). Current models combine more complex processes to better transmit both types of information (Matagne et al., 2020). For a comprehensive review of current coding systems, see Carlyon & Goehring (2021) or Wouters et al. (2015).

All these devices use electrical pulse transmission, the speed of which depends on the technologies and strategies employed . The faster the pulse rate, the closer it gets to the sound coding rate of the healthy ear, but technological limitations mean that increasing the rate reduces the processor’s processing capacity. A balance must therefore be found by the audiologist for each patient to determine the optimal stimulation rate and the most effective strategy (Truy & Lina, 2003).

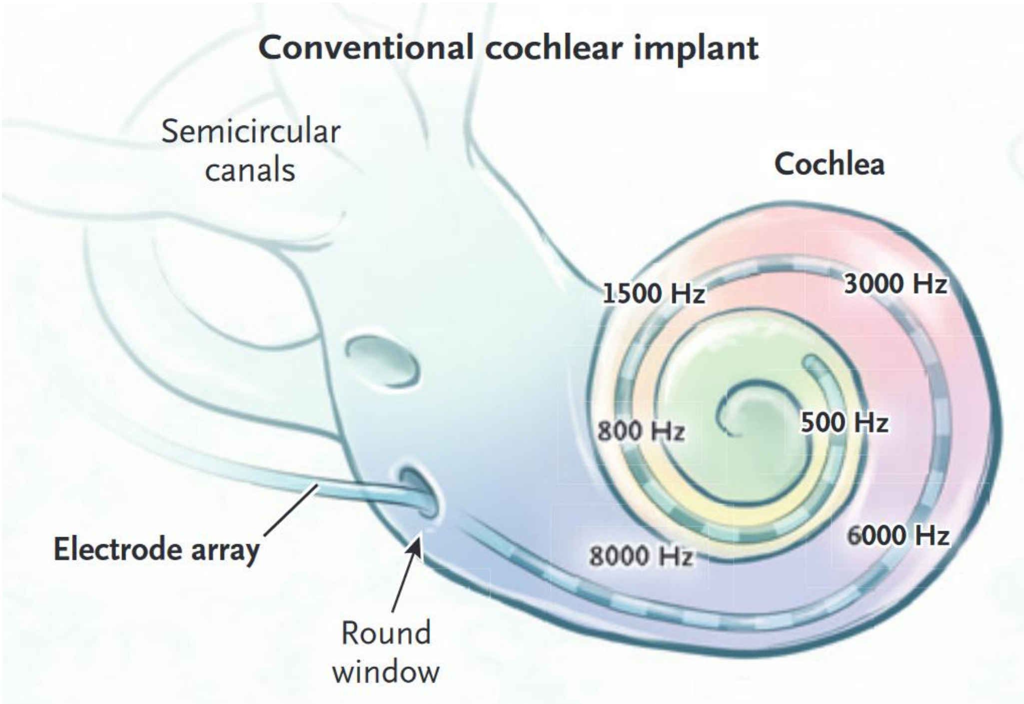

Figure 1.4: Representation of an electrode carrier inserted into the cochlea. From Carlson (2020)

However, as will be described in more detail in Chapter 2, the current cochlear implant, despite the incredible technological advancements it has undergone since its early models, is not capable of accurately transmitting the entire sound signal. Indeed, current technologies cannot entirely replicate the cochlear tonotopy due to the limited number of electrodes capable of transmitting an electrical signal independently, without causing interference between adjacent electrodes (Başkent et al., 2016). Furthermore, the implant is limited in its ability to precisely transmit low and high-frequency information (see figure 1.4). As a result, the signal transmitted by the implant is reduced in spectral resolution, which impacts the ability of its recipients to process speech sounds.

2. Language and communication development in deaf children

To sum up thus far, cochlear implantation can be offered to children with severe to profound sensorineural hearing loss although the implant is not able to transmit all the acoustic information from the captured sound signal, which may impact language development. Before presenting the relevant literature on language and communication development in deaf children, the communication modes available to them will be discussed.

2.1. Communication Modes

In a typically hearing child, the acquisition of language skills usually occurs naturally and without the need for specific adult intervention other than daily oral interactions. The child is born with cognitive processes that will develop and become more complex, provided they are exposed to a rich and complete language environment from an early age through interactions with those around them. In a child born deaf, the development of language and communication skills must be supported through the learning of a gestural communication mode (Sign Language) and/or through the integration of methods that use multisensory stimulation to enhance the perception of spoken language.

Historically, two modes of communication have been in opposition. In the 16th century, Pedro Ponce de León, a Benedictine monk from Spain, developed the first dactylological alphabet based on gestural signs (Martinand-Flesch et al., 2016). The primary objective of this alphabet was to provide an effective communication interface for teaching deaf people to speak. Indeed, according to Spanish law at the time, speaking was necessary to have rights. In the 17th century, Conrad Amman also claimed that speech is essential in the Christian tradition, advocating that God made man in His image, endowed with speech (van den Bogaerde et al., 2016). From the 18th century, the “unmuting” of deaf people was advocated in France, creating the foundations of what is now called the *oralist* approach, aiming for the integration of deaf people into the oral world through auditory and multisensory education, and the use of the first hearing aids. At the same time, Charles Michel de L'Epée opened a school for so-called *deaf-mutes* to teach them the dactylological alphabet and to develop gestural communication incorporating different aspects of the grammar of spoken French. His school received visitors from other countries in Europe and even from the United States, leading to the development of other schools for the deaf that integrated his gestural method. He supported the idea that spoken language is not essential for communication and that gestures can be just as effective in conveying thoughts. According to this vision, he created the National Institute for the Deaf in Paris. The first forms of a community sign language began to develop.

In the 19th century, despite the recognition and adoption of sign language by an increasingly large community worldwide, a school of thought, led notably by Dr. Itard, who was convinced of the necessity of establishing spoken language, banned the use of sign language. During the *Second International Congress of Teachers of Deaf-Mutes*, held in Milan in 1880, the assembly voted to ban the use of sign language and imposed oralist methods as the method of educating deaf children. Following this congress and for about a hundred years, the "pure oralist" method dominated the education of deaf children worldwide, and the use of gestural methods was tacitly prohibited in French institutions. In the 19th century, trends gradually changed due to the observation of severe difficulties in learning spoken and written language through purely oralist education. On the scientific front, linguists began to take an interest in sign languages, highlighting that they are natural languages following a similar acquisition process to spoken language (van den Bogaerde et al., 2016). It was not until 1977 that the use of sign language was reintroduced in France, and the free choice of oral, gestural, or bilingual communication was authorized by the Fabius law in 1991. In Belgium, sign language was recognized by the French Community in 2003 (Moniteur Belge, 2003).

Today, oralist and gestural methods coexist and can be used together. The educational path will depend on the parents' choice. Indeed, the deaf child, due to their lack of auditory input, will have great difficulty, if not an inability, to control what is known as the audio-phonatory loop. The audio-phonatory loop, which depends on the maturation of auditory neural circuits, allows the child to hear and control his own voice. The deaf child, having only limited access to auditory input, does not hear their own productions and, therefore, has great difficulty controlling the parameters (frequency, intensity). Speech development, which occurs naturally in a hearing child, may not occur in a deaf child, leading to what have been called *deaf-muteness*. The child may then spontaneously tend towards gestural communication to interact with their environment (Virole, 2005). An orientation towards communication based on spoken language is only possible with specialized education and appropriate care, which must be provided by the child's environment in collaboration with various professionals (audiologists, speech therapists, psychomotor therapists, etc.), in line with the oralist tradition. These two educational paths can be developed concurrently, leading to bilingualism in spoken and sign language, allowing for early communication through sign language while developing auditory neural circuits and the audio-phonatory loop. The present work will not focus on methods for learning gestural communication, as the objective is centered on the acquisition of a spoken language. It should be noted that this position is entirely scientific in nature; our interest focuses on the mechanisms of acquiring an oral language through limited input and does not have any prescriptive intent regarding the preferred mode of communication between oral and signed languages with deaf children.

Oralist methods, aimed at acquiring spoken language, prioritize multisensory auditory stimulation, relying partly on residual hearing (with or without hearing aids or implants) and partly on other preserved sensory channels, such as vision (lip-reading), kinesthetic and somatosensory sensations (verbo-tonal method), or even gestural methods designed to accompany speech (Cued Speech). Lip-reading enhances phonological discrimination by visualizing articulatory contrasts through lip and jaw movements. Lip-reading allows only a partial perception of speech. However, it is insufficient to gather all the phonetic information necessary to code all the phonological contrasts of spoken languages, as many contrasts (especially those related to voicing, nasality, and backness) are "invisible" due to the limited information from lip movements. Various methods have been developed to promote language emergence despite auditory deprivation and the insufficiency of lip-reading. Notably, the verbo-tonal method, developed in the 1960s by Guberina in Zagreb (Guberina, 1963), is a comprehensive auditory education method based on multisensory stimulation, using vibrating floors, body movements, and speech amplifiers with vibrators. Auditory education activities aim to work on rhythm and melodic variations in both speech and musical contexts (Crnkovic, 2005). Several adaptations of this method have emerged more recently, such as the "Dynamique Naturelle de la Parole" ("*Dynamic Natural*

Speech") method (Dunoyer de Segonzac, 1991) or the "Langue en mouvement" ("*Language in Motion*") method (André-Faber, 2006).

In parallel with these various methods, gestural cueing methods have also been developed, using hand movements to resolve visual ambiguities in lip-reading during speech. The Cued Speech (CS) method was created in 1967 by Cornett in the United States and adapted in France in 1975 (Cornett, 1967). In this method, the spoken sounds are accompanied by manual movements (manual key) positioned at different locations near the face (see Figure 1.5). Words are coded syllable by syllable, with the hand's positioning coding the information related to the vowel produced, while the manuel key codes the information related to the consonant within the syllable. Several consonants are coded with the same cueing gesture, and several vowels are coded with the same hand position to simplify the system, with lip-reading helping to identify the target phoneme among the different candidates.

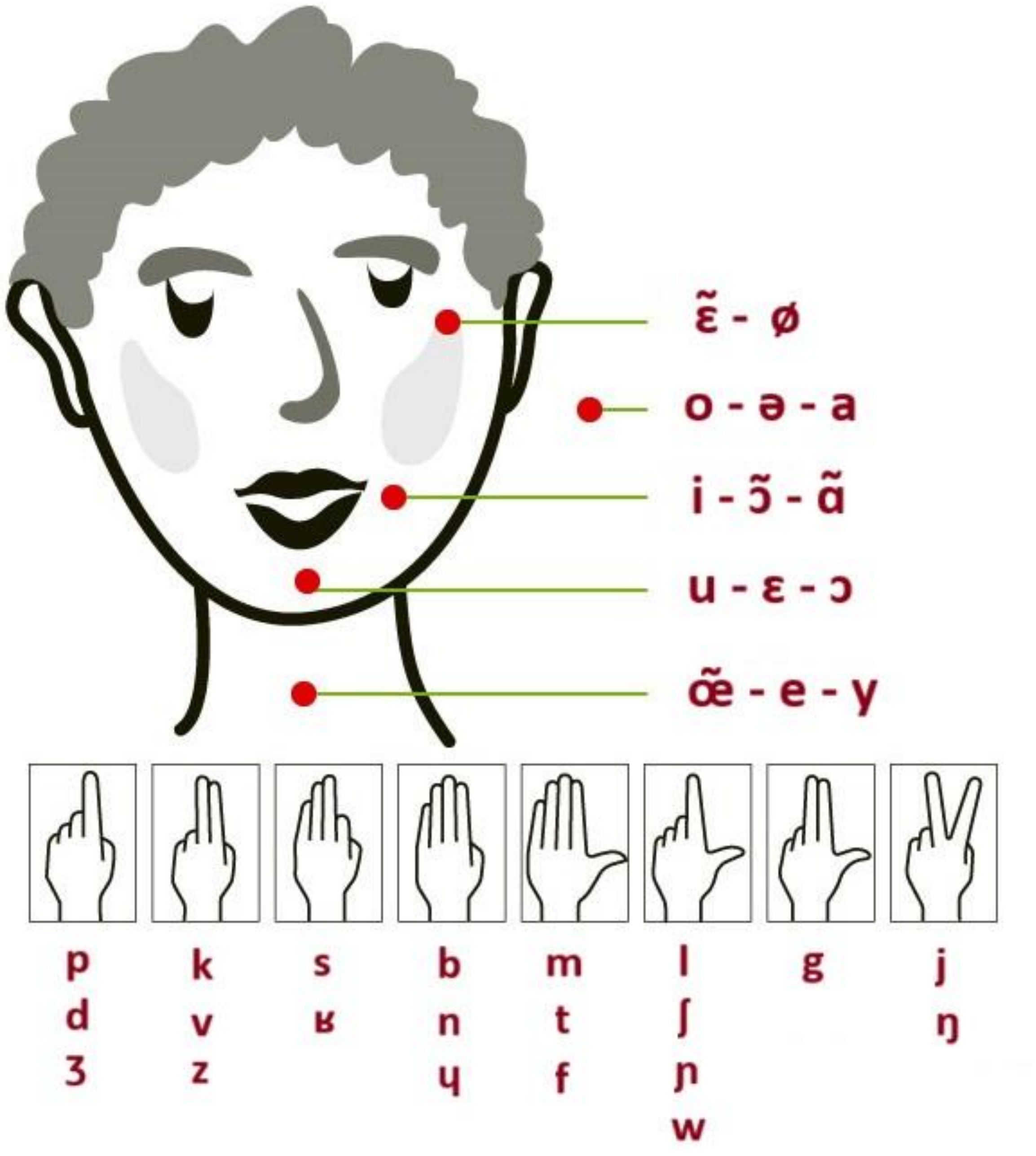

Figure 1.5: Representation of the keys and hand positions used to code consonants and vowels in Cued Speech for French. Adapted from Kiersch (2024)

Thus, the deaf child who perceives Cued Speech hears the spoken sounds and simultaneously visualizes the speaker's lip movements and cueing gestures (Virole, 2005). The goal is for the child to perceive the entire message, with the combination of information from cueing gestures, hand positioning, and lip-reading covering all the phonological contrasts of the language. Numerous experimental studies confirm that Cued Speech is an effective tool for language acquisition (Bouton et al., 2011; Leybaert & LaSasso, 2010; Machart et al., 2024; Van Bogaert et al., 2023).

Whatever communication path is chosen, the goal should be the early rehabilitation of an effective communication system for the deaf child. The present work, aiming to document the development of oral language, will focus on the pediatric population enrolled in education for oral communication or in bilingual communication involving both spoken language and sign language.

2.2. Language development in deaf children with cochlear implants

Despite its undeniable benefits in acquiring sufficient auditory acuity to communicate orally and promoting oral language development, the cochlear implant does not provide a complete auditory signal (Guevara & Macherey, 2018). Furthermore, unlike typically hearing children, who are exposed to linguistic inputs from the intrauterine stage, children with cochlear implants have been exposed to spoken language in a very limited way before their implantation. This delay in exposure to spoken language through auditory inputs may impact the organization of auditory brain areas during sensitive developmental periods, potentially affecting their functioning in the long term and their interactions with language areas (Kral et al., 2016). Numerous experimental studies have examined how children with cochlear implants develop their oral language in this context of delayed and partial exposure to auditory input. In this section, a brief literature review will be presented regarding the main experimental findings across different language components. More comprehensive and specific literature reviews targeting particular aspects of language will be presented within each following chapter.

Given the limitations of the implant in terms of sound transmission, various aspects of perceptual processing and associated phonological skills are likely to be disrupted in children with CI. Several studies have observed difficulties in phoneme discrimination, with increased vulnerability for phonemes whose acoustic correlates are poorly coded by the cochlear implant. Indeed, the cochlear implant is believed to be more effective at transmitting slow-varying temporal acoustic cues, or envelope cues (E cues), as opposed to temporal fine structures (TFS cues), according to the classification of acoustic cues proposed by Rosen (Rosen, 1992). TFS cues are critical for perceiving distinctive features such as the place of articulation of consonants. Therefore, the impact of implant-related perceptual limitations may be selective and depend on the acoustic correlates of the distinctive features which are actually exploited in the phonological system of the child’s native language. Bouton et al. (2012) showed that, in French, children with cochlear implants had increased difficulty discriminating minimal pairs that differed by the place of articulation of consonants or the nasalization of vowels. A greater vulnerability of segments distinguished by fine phonetic cues has also been confirmed in various studies from different languages (Cheng & Chen, 2020; Medina et al., 2004; Moon & Hong, 2014; Peng et al., 2019). Difficulties in distinguishing nasal and oral vowels in the French language were the subject of thorough investigations by Borel (2015; Borel et al., 2019) with adults who used cochlear implants (CIs). These investigations led to the finding that this population has a specific difficulty in distinguishing nasal vowels from phonetically similar oral vowels. This finding was attributed to the specific challenges in processing the fine spectral details of the signal which are precisely associated with nasality.

These findings led to the implementation of Study 1 and Study 2 in the present thesis, which tested the perceptual and productive abilities of children with cochlear implants and their typically hearing peers in the case of French oral and nasal vowels. Study 3 focuses on the production of fricative segments, for which significant difficulties among CI users have been reported in the literature (Giezen et al., 2010; Hedrick et al., 2011; Lane et al., 2001; Mildner & Liker, 2008; Warner-Czyz & Davis, 2008), presumably due to their acoustic correlates being related to high frequencies that approach the limits of the CI device (Loizou, 2006). Study 4 aims to jointly examine the production abilities of both nasal and oral vowels, fricative segments, as well as voiced and voiceless plosive segments within the same group of children. Voiced and voiceless plosive segments were included because their distinction relies on temporal cues that are thought to be better encoded by CIs. The combined study of these three types of segments thus provided an overall view of the children's productive abilities and allows us to compare between segments that are highly contrasted in terms of the quality of the transmission of their acoustic correlates by the implant.

From a lexico-semantic and morphosyntactic perspective, previous studies reported mixed findings as to children with CI: while some studies indicate lexical levels comparable to those of typically hearing children of the same auditory age, grammatical performance, in both perception and production, is more often reported as significantly lower (Caselli et al., 2012; Duchesne et al., 2009; Rinaldi et al., 2013). A discrepancy between the lexical and morphosyntactic language levels has been consistently observed in populations of children with specific language impairments, leading to the development of phonological theories of morphosyntactic difficulties (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992; for a comparison of the theories, see Parisse & Maillart, 2008). According to these theories, phonological difficulties impact the processing of morphemes, particularly grammatical morphemes, which are less perceptually salient and have less conceptual substance than lexical elements of language, making them more vulnerable in cases of phonological challenges. These postulated mechanisms also apply to the population with cochlear implants: perceptual limitations in processing speech sounds most probably result in underspecified phonological representations, which will particularly affect the morphosyntactic level, thereby explaining the findings of lower grammatical performance in the literature. In this context, Study 5 aimed to examine the morphological processing and grammatical production skills of children with cochlear implants (CIs) in comparison to their peers with typical hearing, as well as the connections these skills may have with phonological development on the one hand and lexical development on the other. Finally, Study 6 investigated the link betweeb the acoustic production profiles, as studied in Study 4, and the phonological, lexical, morphological, and morphosyntactic skills identified in Study 5 through factor analyses and the creation of clusters among all the children recruited. A comparison of all performances over a one-year interval have been conducted for a subgroup of children with cochlear implants, allowing for a longitudinal comparison of performance profiles.

The primary objective of this work is to further substantiate the hypotheses linking the linguistic development of children to their specific perceptual limitations. Indeed, significant variability has been reported in studies investigating the different components of language, particularly the morphosyntactic component. Understanding the extent to which this variability can be explained by the level of perception of language contrasts in children would allow for more targeted interventions focusing on these crucial aspects, while ensuring that the interventions are tailored to the specific difficulties encountered by the children.

3. The present work

3.1. Aims

The literature highlights significant variability in the linguistic performance of children with cochlear implants, with increased vulnerability in the development of phonological and morphosyntactic components. These specific difficulties at these levels of language are often attributed to the perceptual limitations associated with cochlear implant technology. However, to our knowledge, no study has directly attempted to link these competencies in an integrative manner, i.e. within the same group of children. Given the variability reported in most studies, it seems valuable to directly investigate these links within a study examining the different components of language in relation to the perceptual profiles of children with cochlear implants.

To this end, we attempted to identify perceptual profiles of children through perceptual tasks (Study 1) and the analysis of their productions (Study 2, 3, 4, 6). Indeed, the perceptual limitations manifested by the processing of speech sounds through the implant should be reflected in their productive profiles, in light of the dichotomy of acoustic cues (TFS vs. envelope cues) observed in experimental studies. Specifically, we aimed to study segments that are more vulnerable due to their acoustic correlates in the French language: nasal and oral vowels. In Chapter 2 and 3, we will see that the mechanisms of perception and production of these segments require the mastery of different classes of acoustic cues, some of which may be more severely affected in children with cochlear implants. Attention will also be given to two types of consonantal segments: fricative segments (Chapter 4), carried by high-frequency cues, and stop consonants, contrasting voiced and voiceless stop consonants, where the distinction is carried by temporal cues. The study of these three types of segments will provide an integrated view of the productive—and, by extension, perceptual—mechanisms in the tested children (Chapter 5). Lexical and morphosyntactic components will be investigated in Chapter 6, and these skills will be connected to the perceptive-productive profiles identified through acoustic investigations in Chapter 7. Within these different studies, the effect of individual and environmental variables will be investigated, specifically chronological/auditory age, age at implantation, and the level of exposure to CS.

3.2. Method

The various studies were conducted through two data collections: the first data collection was carried out to conduct Studies 1 and 2, which focused on investigating the vocalic nasality feature in perception and production, while the second data collection was conducted to investigate all components of language for the following four studies. The section below aims to provide a brief description of the methodological aspects associated with the two data collections. A detailed description will be provided for each study in the corresponding chapters.

3.2.1. Data collection 1

The first data collection was conducted with a group of children with cochlear implants (CI group) and a control group of children with typical hearing (TH group). The CI group consisted of 13 children aged between 5 years 8 months and 11 years 6 months (mean: 8;7 ± 2;4 years) with profound pre-lingual bilateral sensorineural hearing loss. All participants had bilateral cochlear implants (Cochlear brand) implanted between 9 and 30 months of age. The TH group consisted of 25 children aged 5 to 12 years (mean: 8;6 ± 2;4 months), all monolingual French speakers.

Two perceptual tasks were administered:

- A word identification task: Participants were asked to identify target pseudo-words ($C_1V_1C_2V_2$ structure, with vowels being either nasal or oral) within sentences. Eight sentences were constructed, with the pseudo-word placed in either the middle or final position, resulting in a total of 56 items.

- A discrimination task: Participants were presented with pairs of pseudo-words from the identification task. The pairs were designed to evaluate the children's ability to discriminate between nasal and oral vowels based on their phonological or phonetic proximity.

Children completed also a productive task:

- A repetition task: Children were asked to reproduce part of the stimuli from the identification task, specifically the 4 sentences with pseudo-words in the final position (28 items). The experimenter produced the sentences while showing the corresponding pseudo-word card to provide visual cues, and the child was asked to repeat the sentence. Recordings were made using a portable audio recorder.

The results of the two perceptual tasks (identification and discrimination) will be presented in Study 1 (Chapter 2), while the results of the repetition task will be presented in Study 2 (Chapter 3).

3.2.2. Data collection 2

The study involved two groups of children: a group with typical hearing (TH) and a group with cochlear implants (CI). The TH group consisted of 47 monolingual French-speaking children aged 56±13 months. The CI group included 23 French-speaking children (mean age: 67±15 months) with congenital bilateral profound hearing loss, 22 of whom had bilateral implants, and one had a unilateral implant. The information and consent letters provided to the parents of the children are available in Appendices 1 and 2.

The two groups of children completed four tasks:

- Naming Task: This task aimed to document the phonetic, phonological, and lexical skills of the children. Children named pictures representing 48 target words, which covered all French phonemes in various syllable positions. The words were chosen for their early age of acquisition to facilitate retrieval (for a detailed description, see Philippart De Foy et al., 2018). If the child could not produce the target word, semantic and phonological cues were provided, and, if necessary, the experimenter named the word for repetition. The list of words used for the task can be found in Appendix 3.

- Sentence/Word-Picture Matching Task (SWPMT): This task was designed to assess the children's receptive morphological skills. Children were asked to match a word or sentence they heard to a target picture from a pair of images, where the distractor formed a minimal pair with the target. The task included 28 items that varied in grammatical number, gender, and as well as lexical minimal pairs. The variations between the target word/sentence and the distractors were based on different morphophonological alternations: substitutions between nasal/oral vowels, oral/oral vowels, nasal/nasal vowels, or through phonemic additions. The list of target words/sentences and their distractors, as well as an illustration of the testing interface, can be found in Appendix 4.

- Induced and free narrative production tasks: Two narrative production tasks were proposed to study the children's morphosyntactic production skills. In the first task, an induced narrative, a story with animations was presented to the children, who were then asked to retell the story using the animations as visual support. An illustration of the presentation interface and a transcription of the presented narrative can be found in Appendix 5. In the second task, a free narrative, the children were asked to narrate a story from the wordless picture book "Frog, Where Are You?" (Mayer, 1969).

The tasks were administered in a set order: naming, induced narrative, comprehension, and free narrative, over 35 to 60 minutes.

The results of these various tasks will be described in Studies 3, 4, 5, and 6.

3.3. Structure of the thesis

The experimental development of the various questions addressed in this thesis will be presented in the form of six experimental articles. Each article aims to present a specific theoretical context associated with the conducted experiment. Some studies have been published or submitted in referenced journals:

- Study 1, described in Chapter 2 - *Perception of the vowel nasality feature*, was published in the Journal of Speech, Language, and Hearing Research (Fagniart et al., 2024a).
- Study 2, described in Chapter 3 - *Production of oral and nasal vowels*, has been submitted and is currently in press in the Journal of Speech, Language, and Hearing Research (Fagniart et al., in press).
- Study 3, described in Chapter 4 - *Production of fricative consonants*, was published in the proceedings of the Interspeech 2024 conference (Fagniart et al., 2024c).
- Study 4, described in Chapter 5 - *Consonant and vowel production: an integrative study*, was published in Frontiers in Audiology and Otology (Fagniart et al., 2024b).
- Study 5, described in Chapter 6 - *Lexical, morphological and morphosyntactic skills*, will be submitted in Frontiers in Human Neurosciences.

The final study, Study 6, described in Chapter 7 - *Phonetic, phonological, morphologic, lexical and morphosyntactic skills : an integrative study*, will be the subject of a future publication and is currently included in a continuous draft form within this document.

Table 1.1 summarizes the two data collections, the participants, the tasks conducted, the associated studies, and their respective objectives.

The document concludes with a general discussion in Chapter 8, where the findings of the various studies will be synthesized and connected in relation to the research questions.

Data collection	Collection period	Recruitment	Participants	Tasks	Study	Study objective	Type of study	Study sample
1	December 2018 to May 2019	Rehabilitation centers - Schools	13 children with CI - 25 children with TH	Identification and discrimination of pseudowords with nasal and oral vowels	1	Perception of vowel nasality feature	Cross-sectional	All participants
				Repetition of pseudowords with nasal and oral vowels	2	Perceptual judgements and acoustic analysis of nasal and oral vowels productions		
2	February 2020 to November 2023	Rehabilitation centers - Schools - Announcements and word of mouth	23 children with CI - 47 children with TH	Picture naming task	3	Phonological and acoustic analysis of fricative consonants	Cross-sectional	All participants
					4	Integrative study of production of nasal-oral vowels, fricative and stop consonants		
				Picture naming task - word/sentence-picture matching task - Narrative productions	5	Morphemic processing and grammatical production		CI group = 19 (4 bilingual subjects excluded)
					6	Integrative study of acoustic production profiles, phonological, lexical and grammatical skills	Partially longitudinal: retest after one year of a subgroup of children with CI	All for T1 - T2 : 13 children with CI

Table 1.1: Summary of the data collections, participants, administered tasks, associated studies, and their objectives.

Chapter 2 Perception of the vowel nasality feature

This initial study aims to expand on the findings in the literature regarding perceptual difficulties with the vowel nasality feature among French-speaking adults (Borel, 2015; Borel et al., 2019) and children (Bouton et al., 2012) with cochlear implants (CI). The study focuses on comparing the perception of oral versus nasal vowels within different types of nasal-oral pairs (based on their acoustic characteristics) to gain further insight into the specific difficulties related to speech sound processing through cochlear implants. It was conducted as part of the initial data collection involving 13 children with CI and 25 children with typical hearing (TH). The effects of chronological and auditory age, as well as the level of exposure to Cued Speech, is also examined.

This study is published under the reference:

Fagniart, S., Delvaux, V., Harmegnies, B., Huberlant, A., Huet, K., Piccaluga, M., Watterman, I., & Charlier, B. (2024a). Nasal/Oral Vowel Perception in French-Speaking Children With Cochlear Implants and Children With Typical Hearing. *Journal of Speech, Language, and Hearing Research*, *67*(4), 1243-1267. https://doi.org/10.1044/2024_JSLHR-23-00274

The present chapter presents the manuscript in its finalized form.

ASHA American Speech-Language-Hearing Association

JSLHR

Research Article

Nasal/Oral Vowel Perception in French-Speaking Children With Cochlear Implants and Children With Typical Hearing

Sophie Fagniart,[a,b] Véronique Delvaux,[a,b,c,d] Bernard Harmegnies,[b,c] Anne Huberlant,[e] Kathy Huet,[a,b] Myriam Piccaluga,[a,b] Isabelle Watterman,[c,e] and Brigitte Charlier[c,e]

[a] Language Sciences and Metrology Unit, University of Mons, Belgium [b] Research Institute for Language Science and Technology, University of Mons, Belgium [c] Université Libre de Bruxelles, Brussels, Belgium [d] Fund for Scientific Research (F.R.S.–FNRS), Brussels, Belgium [e] Functional Rehabilitation Center "Comprendre et Parler," Brussels, Belgium

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ABSTRACT

Purpose: The present study investigates the perception of vowel nasality in French-speaking children with cochlear implants (CIs; CI group) and children with typical hearing (TH; TH group) aged 4–12 years. By investigating the vocalic nasality feature in French, the study aims to document more broadly the effects of the acoustic limitations of CI in processing segments characterized by acoustic cues that require optimal spectral resolution. The impact of various factors related to children's characteristics, such as chronological/auditory age, age of implantation, and exposure to cued speech, has been studied on performance, and the acoustic characteristics of the stimuli in perceptual tasks have also been investigated.
Method: Identification and discrimination tasks involving French nasal and oral vowels were administered to two groups of children: 13 children with CIs (CI group) and 25 children with TH (TH group) divided into three age groups (4–6 years, 7–9 years, and 10–12 years). French nasal vowels were paired with their oral phonological counterpart (phonological pairing) as well as to the closest oral vowel in terms of phonetic proximity (phonetic pairing). Post hoc acoustic analyses of the stimuli were linked to the performance in perception.
Results: The results indicate an effect of the auditory status on the performance in the two tasks, with the CI group performing at a lower level than the TH group. However, the scores of the children in the CI group are well above chance level, exceeding 80%. The most common errors in identification were substitutions between nasal vowels and phonetically close oral vowels as well as confusions between the phoneme /u/ and other oral vowels. Phonetic pairs showed lower discrimination performance in the CI group with great variability in the results. Age effects were observed only in TH children for nasal vowel identification, whereas in children with CIs, a positive impact of cued speech practice and early implantation was found. Differential links between performance and acoustic characteristics were found within our groups, suggesting that in children with CIs, selective use of certain acoustic features, presumed to be better transmitted by the implant, leads to better perceptual performance.
Conclusions: The study's results reveal specific challenges in children with CIs when processing segments characterized by fine spectral resolution cues. However, the CI children in our study appear to effectively compensate for these difficulties by utilizing various acoustic cues assumed to be well transmitted by the implant, such as cues related to the temporal resolution of stimuli.
Supplemental Material: https://doi.org/10.23641/asha.25328704

1.Introduction

In recent decades, numerous studies have examined the language development of deaf children who have received cochlear implants. These devices have proven to be highly beneficial for acquiring or restoring functional hearing acuity and developing oral language (Tamati et al., 2022). However, research has consistently highlighted substantial variability in performance, particularly in speech perception skills, which often do not reach the level of typically hearing peers. Several factors contribute to the remaining perceptual difficulties of CI users.

1.1. Limitations of sound transmission through the implant

The primary limiting factor is the way in which the implant transmits sound. The sound signal passing through the implant undergoes various transformations, including bandpass filtering, envelope extraction, and low-pass filtering within the processor (Guevara & Macherey, 2018). These transformations reduce spectral information, particularly temporal fine structures (TFS) (Moon & Hong, 2014). The resulting sound is then transmitted to the neurons of the spiral ganglion through different electrodes positioned along the basilar membrane. The arrangement of these electrodes partially recreates cochlear tonotopy, with low-frequency information transmitted by electrodes farthest from the base (stimulating apical regions) and high-frequency information handled by electrodes in contact with basal regions. However, the number of electrodes capable of independently transmitting auditory information is limited due to activation diffusion and interactions between adjacent electrodes (channel-to-channel interactions). Moreover, the position of the electrode array within the cochlea can further influence the quality of the transmitted signal. The depth of electrode array insertion impacts the covered frequency range, with low-frequency coding depending on the shallow of the array insertion and potential misalignments in frequency mapping (Başkent & Shannon, 2005). These factors collectively exert a notable influence on speech perception outcomes (Canfarotta et al., 2021; Fan et al., 2023; Mertens et al., 2022). Additional sources of inter-individual variability in sound processing quality include the presence of residual hearing in low-frequency areas, the integrity of auditory nerve cells, anatomical and surgical abnormalities, and device-specific characteristics, such as sound-coding strategies (for a description, see Başkent et al., 2016).

1.2. Spectral resolution and speech sound processing in cochlear implant recipients

Many studies have aimed to understand how adults and children with cochlear implants process spectral resolution, in comparison to their typically-hearing counterparts. These investigations typically employ perceptual paradigms using synthesized sounds, such as the Spectral/Temporal Modulated Ripple Test (Aronoff & Landsberger, 2013), which involves tasks like rippled noise discrimination. Research reveals that spectral resolution processing undergoes age-related changes in typically-hearing children (DiNino & Arenberg, 2018; Horn et al., 2017; Jahn et al., 2022). Conversely, children with cochlear implants often exhibit lower performance in spectral resolution (Henry & Turner, 2003), and their performance doesn’t consistently correlate with age or auditory experience with the implant (DiNino & Arenberg, 2018; Horn et al., 2017; Landsberger et al., 2018). These findings suggest that the information provided by the implant alone may be insufficient for the development of adequate spectral resolution skills in children. Landsberger et al. (2018) investigated spectral resolution processing in adults and children to understand how their perceptual systems adapt to degraded auditory signals. The results show that pediatric CI recipients have lower spectral resolution abilities compared to post-lingually implanted adults, emphasizing the importance of prior auditory experience. However, unlike adults, children do not consistently link speech perception performance with spectral resolution scores (Gifford et al., 2018), suggesting that they can develop perceptual skills in the absence of optimal spectral processing, possibly relying on other acoustic cues. Additionally, Landsberger et al. (2018) observed different effects of bilateral implantation on spectral resolution skills in post-lingually implanted adults and children with early implanted children. While adults might exhibit a detrimental effect of spectral processing when listening through both of their implants, which could be attributed to challenges in integrating potential frequency misalignments between the two ears, children, on the contrary, showed improved performance in bilateral listening conditions. These findings support the idea that early implantation helps congenitally deaf children adapt to degraded acoustic signals by extracting relevant information for speech sound discrimination in their language. Children may rely more on temporal information in the signal, as confirmed in a study of Landsberger et al. (2019), where children with cochlear implants showed superior temporal modulation detection compared to adult CI recipients.

1.3. Impact on speech processing

Acoustic limitations affecting spectral resolution impact the processing of speech by CI user. For example, it has been demonstrated in studies examining vocal gender identification and/or speaker discrimination based on characteristics such as vocal-tract length (VTL). Indeed, CI users appear to have more difficulty processing VTL-related cues precisely, presumably because this processing relies on good spectral skills (Gaudrain & Başkent, 2018).

Moreover, the difficulties in processing certain types of acoustic information may explain performance patterns in the processing of speech contrasts by individuals with CI. Indeed, some phonological features, such as the voicing feature or manner of articulation within consonants, seem to cause fewer perceptual difficulties than the features of place of articulation or nasality within vowels and consonants (Bouton et al., 2012; Grandon et al., 2017; Medina & Serniclaes, 2009; Pisoni et al., 1999). Some authors (Bouton et al., 2012; Cheng & Chen, 2020; Peng et al., 2019) attribute these patterns of difficulties to the fact that different phonological features are carried by specific acoustic information, some of which may be well transmitted by the implant (slowly varying envelope cues) and others not (temporal fine structures cues), following the dichotomy of the acoustic cues proposed by Rosen (1992). This dichotomy in the types of cues used by the pediatric CI population has been confirmed in several studies (Cheng & Chen, 2020; Moon & Hong, 2014; Peng et al., 2019). Although allowing access to sufficient acoustic input to acquire most phonological contrasts, CI may not be sufficient in processing phonetic details associated with certain phonological features. In this paper, we will focus on one of those phonological features which phonetic implementation relies on precise spectral processing, namely the [nasal] feature for French vowels.

1.4. Nasal vowels : phonology and phonetics

Vocalic nasality occurs when the velopharyngeal port opens during vowel production, allowing coupling between the oropharyngeal and nasal tracts, thereby adding nasal resonances and anti-resonances to the vocal tract transfer function. In many languages, vocalic nasality is a phonetic phenomenon associated with coarticulation, whereby a nasal consonant follows and/or precedes an oral vowel, and the nasal and oral gestures overlap. While the nasalization that occurs in such cases isn’t contrastive, it serves as a useful cue during speech perception. However, in French, as in nearly 30% of the world languages (e.g. Portuguese, Polish or Hindi; Styler, 2017), vowel nasality is phonological, i.e. nasal vowels contrast with oral vowels in minimal pairs and the [nasal] feature is a constituent of the phonological system.

The French language has four nasal vowels in its vocalic system: the open back nasal vowel /ɑ̃/; the mid-open front nasal vowel /ɛ̃/; the mid-open rounded back nasal vowel /ɔ̃/; and the mid-open front nasal vowel /œ̃/. It is noteworthy that the distinction between /ɛ̃/ and /œ̃/ is progressively disappearing in French, in favor of the anterior variant (Borel, 2015; Fougeron & Smith, 1993). To avoid specificities related to the regional origin of the participants, and for the sake of simplicity, we will only focus on the nasal vowels /ɑ̃/, /ɔ̃/ and /ɛ̃/ in the present paper. Within the French phonological system each of these nasal vowels contrasts with an oral counterpart based on the sole [nasal] feature: /ɑ̃/-/ɑ/, /ɔ̃/-/ɔ/, and /ɛ̃/-/ɛ/. This phonological opposition supports a large array of morpho-phonological alternations in French grammar ("paysan/paysanne": /ɑ̃/-/an/, "bon/bonne": /ɔ̃/-/ɔn/, "vilain/vilaine": /ɛ̃/-/ɛn/). Thus, in cases of difficulty in perceiving vocalic nasalization, these oral vowels may be good candidates for substituting their corresponding nasal counterparts.

However, this phonological opposition between oral and nasal vowels, which is functionally and historically anchored, is not necessarily consistent with empirical data regarding the phonetic differences between nasal and oral vowels. Indeed, different authors (Carignan, 2014; Delvaux, 2012; Maeda, 1993; Montagu, 2007) have observed that nasal vowels and their corresponding oral phonological counterparts differ not only in terms of nasality but also in terms of their oro-pharyngeal articulatory configuration (positioning of the lips and tongue). This phenomenon can be explained by the chain shifts that can occur in the world's languages and that have led, here in the French language (Fagyal et al., 2006), to modifications in the phonetic realization of nasal vowels, which have deviated from the classical description set in phonology. These observations are supported by the various acoustic studies carried out around these pairs of nasal-oral vowels. Montagu (2007), for example, isolated the first non-nasalized portions of nasal vowels (portions corresponding to a delayed opening of the velum) produced by French-speakers, and had them identified by listeners. The listeners identified the portion of nasal vowel [ɑ̃] as [ɔ], [ɛ̃] as [a], and [ɔ̃] as [o], suggesting that the oral vowels /ɔ, a, o/ seem to be the closest phonetic counterparts of nasal vowels /ɑ̃, ɛ̃, ɔ̃/. Carignan (2014) conducted an acoustic study of the formant patterns of nasal vowels and their corresponding oral phonological counterparts with different French-speakers. The author observed that the acoustic productions of nasal vowels differ from those of their oral counterparts, following modifications of labial and/or lingual articulator configurations. Carignan proposed a revision of the phonetic notations of French nasal vowels in the International Phonetic Alphabet (IPA) that is more faithful to the actual acoustic realization of these vowels: [ɑ̃] revised to [ɔ̹̃], [ɛ̃] to [ɐ̃], and [ɔ̃] to [õ̹].

Considering only the phonetic aspects of vowel nasalization - i.e. those associated with velopharyngeal opening independently of other articulatory adjustments - the study of the acoustic effects of nasal resonance presents a challenge for researchers, as the acoustic coupling of nasal cavities with pharyngeal and oral cavities generates a complex resonance system (Delvaux, 2012). Nasal resonance involves numerous acoustic changes in the spectrum of a vowel, resulting in multiple but subtle changes throughout the frequency range, with the most critical for perception occurring in the low frequencies. Many authors have attempted to identify the acoustic cues most relevant for vowel nasalization, without successfully identify a common property, shared across different languages and little sensitive to inter-speaker variations. To name just a few, nasal resonance has been reported to influence the frequency and intensity of F1 (Delattre, 1954) but also an increase of F1 (and F3) bandwidth (Delvaux, 2002, 2012), with a decrease in the overall vowel intensity (House & Stevens, 1956; Maeda, 1993). Maeda (1993) reports that the main cue of vowel nasality is carried by the flattening of spectral peaks around F1 and F2, resulting in a widening of the first peak or the addition of a formant around this first spectral peak. Based on perceptual studies using semi-synthetic stimuli, Delvaux (Delvaux, 2002; Delvaux et al., 2004) proposes that the Compactness of the vowel (operationalized as an increase in bandwidths of F1 and F3 with respect to that of F2) leads to the perception of phonetic nasality. Chen (1995, 1997) identifies that nasal resonance, associated with the appearance of nasal poles and zeros, leads to a change in the relative intensity levels between the first harmonics and the first formant. To quantify these changes, Chen developed the measures A1-P0 and A1-P1, which measure the relative amplitude deltas between the first formant and the first (for A1-P0) and second (for A1-P1) nasal pole. Although not without flaws (especially for high vowels), these measures are the most widely used nowadays to characterize phonetic vowel nasalization.

To sum up, the acoustic correlates associated with nasal resonance are complex and require the ability to precisely process acoustic information with a certain degree of frequency selectivity and sensitivity to amplitude variations, especially among low-frequency harmonics. Due to a deficit in frequency selectivity related to electrode spacing on the basilar membrane, the potential frequency compression in low frequencies and the lower spectral resolution of the sound transmitted, the distinction between nasal and oral vowels is likely to be a source of perceptual difficulty for cochlear implant users. To date, only a limited number of studies have addressed this issue.

1.5. Cochlear implant and nasality perception

In 2012, Bouton et al. conducted a study to evaluate the perception abilities of different phonetic features in French consonants and vowels, such as nasality, among children CI users. The study involved minimal pair identification and discrimination tasks with 25 children between 7 and 12 years old with bilateral profound deafness and wearing unilateral CI. Twenty-five typical hearing (TH) children were also included in the study as age-matched controls. The results showed significantly lower scores in the CI users' group, for both consonants and vowels. However, the differences between the two groups were more pronounced for certain features, such as place of articulation for consonants, but especially for nasality which caused more errors within consonants and vowels. The authors justify the increased difficulty in perceiving the features of nasality and place of articulation by the fact that they could be carried by temporal fine structure (TFS cues; Rosen, 1992), unlike voicing and manner of articulation features which would be carried by the temporal envelope of the signal (E cues; Rosen, 1992), and therefore better transmitted by the CI. The authors suggest that children with CI exhibit lower spectral resolution abilities, particularly in the low frequencies, which may have a greater impact on nasal vowels, as these present additional poles and/or zeros in F1 vicinity.

Borel (2015) and Borel et al. (2019) has conducted various studies on the perception of vowel nasality among French-speaking adult CI users. In a first study, 82 severely deaf adult participants with unilateral (n=76) and bilateral (n=6) CI showed significantly lower performance compared to their hearing peers in identifying nasal vowels in a phonemic identification task, perceiving them as oral vowels, regardless of their age or their CI use duration. Borel (2015) continued her investigation with a discrimination task of oral and nasal vowel pairs in 15 unilaterally CI adult and 6 typical hearing (TH) participants, involving "phonological" pairs based on the classical morpho-phonological opposition described above (/ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/), and "phonetic" pairs contrasting nasal vowels with the oral vowels that are phonetically closest to them based on the literature and the author's clinical experience (/ɑ̃/-/ɔ/, /ɔ̃/-/o/, /ɛ̃/-/a/). The results confirm that the CI participants have significantly lower performance than TH subjects for both types of oral-nasal pairs, and that phonetic pairs are significantly less recognized than phonological pairs. By examining the characteristics of the stimuli used in the discrimination task, the author observed that the vowels in the so-called "phonetic" nasal/oral pairs were very similar in terms of spectral peaks, the differences being mainly differences in relative intensity between the low-frequency peaks. Considering the limitations in spectral processing associated with the implant, phonetic pairs are therefore more likely to cause difficulties for CI recipients than phonological pairs, leading to more difficulties in discrimination tasks and more substitution errors during identification tasks.

1.6. Inter-subject influencing factors in sound processing

Several factors are known to be key influencers of language performance in general, and speech perception in particular, for children with cochlear implants. Among these, the age of implantation stands out as a critical determinant. Early implantation is essential to ensure the optimal development of cortical areas dedicated to auditory signal processing and speech perception during sensitive periods of development (Gao et al., 2021; Kral et al., 2019; Sharma et al., 2020). Auditory experience also plays a crucial role, as evidenced by the positive effects of the duration of cochlear implant use in both adults (Holder et al., 2020) and children (Park et al., 2019), as well as the influence of chronological or auditory age (Dunn et al., 2014). The quantity and quality of language stimulation before and after implantation are other crucial factors in enhancing perceptual skills (Sharma et al., 2020). Some language rehabilitation tools also have an impact on perceptual abilities. For example, Cued Speech (Cornett, 1967) is a manual code used in addition to spoken language to supplement the lipreading, aiming to enable visual access to all distinctive features of speech sounds. Its integration into the care and communication of children with cochlear implants has been recognized as having positive effects on speech perception (Bouton et al., 2011; Leybaert et al., 2016; Leybaert & LaSasso, 2010; Van Bogaert et al., 2023) and speech production (Machart et al., 2021).

1.7. Aims of the study

The studies by Bouton et al. (2012) and Borel (2015, 2019) highlight difficulties in perceiving the distinction between nasal and oral vowels among French-speaking adults and children CI recipients. However, it's worth noting that both studies focused on unilaterally implanted recipients. In contrast, bilateral cochlear implantation has been reported as beneficial for speech perception (Anand et al., 2022; Caselli et al., 2012; Sarant et al., 2014; Sharma et al., 2020; Zeitler et al., 2008) even in noise (Dunn et al., 2010; Müller et al., 2002), but also in terms of spectral resolution (Landsberger et al., 2018). Given that perceiving vowel nasality requires precise spectral resolution, one can assume that bilateral implantation could have a positive impact on the processing of this phonetic feature in French-speaking children. Moreover, the phonological vs. phonetic proximity effect suggested by Borel (Borel, 2015) in adults seems very interesting to investigate in children. It has been shown that children, even without the experience of hearing undegraded signals, may develop enhanced skills in processing degraded auditory signals due to early implantation (Landsberger et al., 2018). As a result, children could exhibit different response patterns to adults because they exploit acoustic cues differently. Additionally, we lack data regarding open-set identification of nasal vowels in children. A fuller description of the types of error they make most often would provide a better understanding of the processing (dis)similarities underlying their difficulties. Similarly, an analysis of perceptual performance in relation with the acoustic characteristics of the stimuli should provide further insight into the specific cues CI children recipients use to process vowel nasalization. In this context, the present study pursues several objectives:

- Our first aim is to compare the performance of groups of French-speaking children with bilateral cochlear implants to that of children with typical hearing in the processing of contrastive vowel nasalization. Given the limitations of acoustic processing in cochlear implants, we may expect poorer performance in implanted children, as observed in previous literature. However, bilateral and early implantation could be positive factors influencing processing skills, which might bring the performance closer to that of children with typical hearing. Furthermore, we consider here several inter-individual factors known to influence speech perception and spectral resolution processing. Within the two groups, we thus formed groups based on chronological age, as well as auditory age for implanted children. For the children with implants, we also study whether sustained exposure to Cued Speech (CS) and early implantation (< 10 months) are associated with better performance.
- In light of the results obtained by Borel (2015) with implanted adults, we aim to investigate the differential impact of phonological vs. phonetic proximity within pairs of nasal and oral vowels in children with CI. We

hypothesize that in identification tasks, children may be more inclined to substitute nasal vowels with their phonetically similar oral counterparts and may have lower performance in discriminating phonetically close nasal/oral pairs, similar to the implanted adults in Borel's (2015) study. However, these difficulties may be more compensated for in children whose phonological system has developed based on linguistic input degraded by the implant, as suggested by Landsberger (2018).

- The literature suggests that children developing their phonological system through a cochlear implant make differentiated use of the different acoustic cues available to support certain phonological contrasts. The present study aims at exploring this possibility in the case of distinctive vowel nasalization, a contrast which relies on fine spectral resolution skills, by analyzing which acoustic features of the stimuli are best related to children's performance in our perceptual tasks. More specifically, we have measured a variety of acoustic cues related to overall vowel intensity, fine spectral properties (formant frequencies, bandwidths, and amplitudes; nasal poles) and temporal envelope. Children with cochlear implants who rely more on cues better encoded by the implant (such as temporal envelope) can be expected to perform better in perceptual tasks.

2. Method

2.1. Participants

The study was conducted with two groups of children aged between 5 and 12 years old: a group of children with hearing loss and wearing bilateral cochlear implants (CI group) and a control group of children with typical hearing (TH group). The CI group included 13 children (7 girls and 6 boys), aged between 5;8 years and 11;6 years (mean: 8;7 ± 2;4 years), with prelingual bilateral profound hearing loss. All children of the CI group used bilateral cochlear implants (implanted between 9 and 30 months, mean: 13;7 ± 6 months). Children who were implanted before the age of 10 months were considered to be early implanted (recent studies have shown that implantation before 10 months allows for more natural language development, Karltorp et al., 2020), and there were 7 of them in the sample. Their vocal audiometry curve with CI for word/pseudoword repetition ranged from 88% to 100% at 55/60 dB. All of them received an oralist auditory rehabilitation, both in their rehabilitation center and in their family context. We have taken into account the level of Cued Speech (CS) exposure: 6 of the children are exposed occasionally (during their speech therapy sessions with an average of

3 sessions per week but not in their home environment) whereas 7 have been exposed early in their development and intensively (in their family context as well as during their speech therapy sessions). More specifically, parents of children with early and sustained exposure have been trained to code in CS and appreciate the importance of using it to support spoken language. CS was used on a daily and sustained basis from an early age, but for some to a lesser extent as the children were able to use their implants appropriately. The list of participants and their characteristics are presented in Table 2.1.

Subject	Sex	Chronological age (years ; months)	Chronological age group	Auditory age group	Age at implantation (months)	Implantation age group	Cued speech exposure
CI1	M	5;11	4-6y.	4-6y.	12	>10m.	Occasionnal
CI2	M	5;10	4-6y.	4-6y.	9	≤10m.	Early&frequent
CI3	M	6;8	4-6y.	4-6y.	10	≤10m.	Early&frequent
CI4	F	6;10	4-6y.	4-6y.	13	>10m.	Early&frequent
CI5	M	6;11	4-6y.	4-6y.	10	≤10m.	Early&frequent
CI6	F	8;6	8-9y.	4-6y.	19	>10m.	Occasionnal
CI7	F	8;8	8-9y.	8-9y.	12	>10m.	Early&frequent
CI8	M	9;7	8-9y.	8-9y.	9	≤10m.	Occasionnal
CI9	F	10;8	10-12y.	8-9y.	19	>10m.	Occasionnal
CI10	M	10;8	10-12y.	8-9y.	10	≤10m.	Occasionnal
CI11	M	10;11	10-12y.	10-12y.	10	≤10m.	Occasionnal
CI12	F	11;5	10-12y.	10-12y.	12	>10m.	Early&frequent
CI13	F	11;6	10-12y.	10-12y.	30	>10m.	Early&frequent

Table 2.1: Characteristics of the CI children.

The TH group consisted of 25 children (11 girls and 14 boys) aged 5 to 12 years old (mean: 8; 6 ± 2;4 years). Subjects who received or were undergoing speech therapy were excluded during recruitment. Three age subgroups were formed: 4-6 years old, 7-9 years old, and 10-12 years old. To compare the effect of the two kinds of grouping, the CI children were grouped on their chronological age as well as on their auditory age (Table 2.1). The TH children were grouped only on their chronological age.

Group	Number of participants	Mean age (years ; months)	Chronological age subgroups	Auditory age subgroups
CI group	13	8 ; 7	4-6 years (3), 7-9 years (6), 10-12 years (4)	1-2 years (7), 3-4 years (3), 5-6 years (3)
TH group	25	8 ; 6	4-6 years (9), 7-9 years (8), 10-12 years (8)	N/A (typical hearing)

Table 2.2: Age characteristics of main groups (CI and TH) and subgroups based on chronological or auditory age.

2.2. Stimuli

2.2.1. Stimuli construction

The stimuli consisted of C1V1C2V2 pseudowords where C1=C2=/t/ and V1=V2= /ɑ̃, ɔ̃, ɛ̃, a, ɔ, ɛ, u/. The phonological and phonetic correspondences for each nasal are reported in Table 2.3.

Nasal target	Oral phonological correspondent	Oral phonetic correspondent
/ɑ̃/	/a/	/ɔ/
/ɛ̃/	/ɛ/	/a/
/ɔ̃/	/ɔ/	/u/

Table 2.3: Nasal targets and their corresponding oral phonological and phonetic counterparts.

Note that for the nasal /ɔ̃/, phonotactic rules (position law: Fougeron and Smith, 1993) prevent the creation of stimuli with identical syllabic structure bearing the semi-open /ɔ/ vs. semi-closed /o/. In an open syllable, only the sequence /toto/ is possible, typically realized as [to̜to̜] in Belgian French. Consequently, the considered phonetic correspondence for this study is the high vowel /u/. Note that this choice is entirely congruent with the data of Carignan (2014). Indeed, based on acoustic analyses of nasal and oral vowel productions in French, it was observed that the oro-pharyngeal configuration of the nasal vowel [ɔ̃] corresponded more closely to the production of the oral vowel [o] with higher tongue position (Carignan thus proposes the phonetic notation [õ̝]). The phoneme /u/ is the French vowel closest to this articulatory configuration and is therefore a relevant oral phonetic counterpart. The constructed stimuli were thus /tɑ̃tɑ̃/, /tɔ̃tɔ̃/, /tɛ̃tɛ̃/, /tata/, /tɔtɔ/, /tɛtɛ/, /tutu/. These pseudowords were produced repeatedly by a male speaker and recorded in a soundproof room. One iteration per item was selected as being the most neutral in terms of prosody with typical articulation. Within the selected items, vowels were normalized in terms of durations (V1: 100 ms; V2:

150 ms) intensity (mean value : 72 dB) and pitch (mean value : 122 Hz) using PRAAT Toolkit (Corretge, 2019).

2.2.2. Acoustic characteristics of the stimuli

Table 2.4 presents the acoustic characteristics of the 7 target vowels extracted from the stimuli, in medial (vowel 1) and final (vowel 2) positions. We collected a series of acoustic features that have been documented as being associated with the distinction between oral and nasal vowels (for a complete review, see Styler, 2017) : 1) the frequency values of the first three formants, 2) their bandwidths and 3) their amplitudes, 4) A1-P0 and A1-P1 values (demonstrated to be associated with nasal resonance – Chen, 1995, 1997 ; Styler, 2017) and 5) the overall vowel intensity. All these measures were taken in the middle of the most stable portion of the vowel using a PRAAT script adapted from the one provided by Styler (2017).

	Vowel	F1 (Hz)	bF1 (Hz)	aF1 (dB)	F2 (Hz)	bF2 (Hz)	aF2 (dB)	F3 (Hz)	bF3 (Hz)	aF3 (dB)	A1-P0 (dB)	A1-P1 (dB)	Intensity (dB)	ENV (dB)
Vowel 1	**/ɑ̃/**	448	239	40,3	964	395	28,9	2520	631	9,2	-1,69	14,75	0,057	307,00
	/ɛ̃/	457	232	41,2	1445	204	26,4	2604	731	15,5	-2,00	19,10	0,076	377,00
	/ɔ̃/	336	174	41,7	1285	851	7,9	2783	269	9,6	-2,27	33,29	0,088	398,00
	/a/	560	41	44,6	1440	161	28,5	2676	510	19,3	5,18	24,01	0,089	479,00
	/o/	379	64	45,4	1162	550	19,7	2584	405	12,8	4,01	28,27	0,079	272,00
	/u/	345	131	42,6	1171	181	8,7	2136	375	11,4	0,33	27,59	0,069	193,00
	/ɛ/	310	36	45,4	1846	241	22,0	2575	477	18,0	2,88	35,86	0,101	477,00
Vowel 2	***/ɑ̃/***	444	232	41,0	1072	422	24,5	2554	664	7,1	-3,07	22,31	0,066	542,00
	/ɛ̃/	379	371	40,2	1430	300	25,7	2639	2667	11,7	-3,22	16,44	0,053	459,00
	/ɔ̃/	340	158	43,4	1183	1405	13,0	2245	550	7,2	-1,88	31,99	0,081	461,00
	/a/	551	54	47,8	1332	166	28,9	2678	267	21,9	4,83	20,09	0,088	811,00
	/o/	358	81	45,6	1026	436	22,7	2641	504	7,3	2,18	27,27	0,075	601,00
	/u/	329	194	44,9	1153	592	11,2	2034	652	4,5	-2,29	31,79	0,068	498,00
	/ɛ/	336	31	47,1	1829	309	22,7	2501	730	17,0	4,27	36,29	0,091	775,00
	Nasal-Oral	NS	*.003*	*.001*	NS	NS	NS	NS	NS	NS	*.008*	NS	NS	NS

Table 2.4: Acoustic characteristics of target vowels in both syllable positions (medial and final). Last line indicates the level of significance of a Mann-Whitney test conducted between nasal and oral vowels.

In order to compare the acoustic characteristics of oral and nasal vowels in our stimuli, the two groups of vowels were first compared using Mann-Whitney tests on all these measures. It can be observed that only the bandwidth and amplitude values of F1, along with the A1-P0 values, demonstrate a significant difference between nasal and oral vowels considered as a group (see Table 2.4), which is congruent with the literature (see section 1.1). As a second step, we calculated the difference between the acoustic values of the two members of each phonetic and phonological pair (Table 2.5). For the formant values, we also computed the Euclidean distance between the two vowels of each pair in the F1-F2 space. Since it is a parameter that may be preferentially utilized in children with cochlear implants, the temporal envelope of the vowel productions was compared within pairs using the "Envelope Index Difference" (Fortune et al., 1994) with a script developed by Nambi (2023). We used the intermediate values of envelope amplitude means to further characterize the vowels in Table 2.4. The Mann-Whitney tests comparing the phonetic and phonological pairs on the various differential parameters reported in table 2.5 show a significant difference only in the Euclidean distances in the F1-F2 space. This difference confirms that the phonological pairs indeed differ from the phonetic pairs in their oro-pharyngeal configuration, as expected. Spectral representations of nasal vowels and their phonetic and phonological correspondents are available in Appendix 1.

	Pair type	Pair	Δ F1	Δ bF1	Δ aF1	Δ F2	Δ bF2	Δ aF2	Δ F3	Δ bF3	Δ aF3	D.E. F1/F2	Δ A1-P0	Δ A1-P1	Δ Intensity	EDI
Vowel 1	***Phonological***	***/ã/-/a/***	-112	198	-4,3	-476	235	0,4	-155	121	-10,1	489	-6,87	-9,27	-0,031	0,11
		/ɔ̃/-/ɔ/	-43	110	-3,8	483	300	-11,7	199	-137	-3,3	130	-6,28	5,02	0,009	0,06
		/ɛ̃/-/ɛ/	146	196	-4,2	-401	-37	4,4	29	254	-2,5	427	-4,89	-16,77	-0,025	0,04
	Phonetic	***/ã/-/ɔ/***	69	175	-5,1	-198	-155	9,3	-64	226	-3,6	209	-5,70	-13,53	-0,022	0,13
		/ɔ̃/-/u/	125	42	-0,9	339	-1040	-0,8	615	-106	-1,9	114	-2,59	5,70	0,019	0,06
		/ɛ̃/-/a/	-103	191	-3,4	4	44	-2,1	-72	222	-3,8	103	-7,18	-4,92	-0,012	0,07
Vowel 2	***Phonological***	***/ã/-/a/***	-108	178	-6,8	-260	256	-4,5	-123	397	-14,7	281	-7,90	2,22	-0,022	0,09
		/ɔ̃/-/ɔ/	-18	78	-2,3	157	969	-9,7	-396	45	-0,1	158	-4,06	4,72	0,006	0,08
		/ɛ̃/-/ɛ/	43	340	-6,9	-398	-10	3,0	138	1937	-5,3	401	-7,49	-19,85	-0,038	0,12
	Phonetic	***/ã/-/ɔ/***	86	152	-4,7	46	-14	1,8	-86	160	-0,1	97	-5,25	-4,96	-0,009	0,13
		/ɔ̃/-/u/	95	-36	-1,5	-577	813	1,8	-560	-102	2,7	32	0,41	0,20	0,013	0,07
		/ɛ̃/-/a/	-172	317	-7,5	99	133	-3,3	-38	2400	-10,2	199	-8,05	-3,65	-0,035	0,05
	Phonological-Phonetic		NS	NS	NS	NS	NS	NS	NS	NS	NS	***.026***	NS	NS	NS	NS

Table 2.5: Distances between the various acoustic indices among the members of different pairs in the discrimination task. Last line indicates the level of significance of a Mann-Whitney test conducted between phonological and phonetic pairs.

2.3. Experimental tasks

2.3.1. Identification

The identification task consisted of presenting a sentence in which the CVCV pseudoword target was embedded. The sentences were naturally produced by the same male speaker as the pseudowords. Four pairs of carrier sentences were structured so that the pseudoword was placed in two different prosodic positions (for example: “I saw /tɑ̃tɑ̃/ near the bus” or “Near the bus, I saw /tɑ̃tɑ̃/”), for a total of 56 sentences (8 carrier sentences * 7 target pseudowords; the 7 pseudowords remained identical across the different sentences). The choice of placing pseudowords in two positioning was made in order to generate more stimuli without multiplying the carrier sentences to avoid overburdening the task for children. The carrier sentences were deliberately constructed to exclude nasal vowels and to maintain a concise length of 7 to 8 syllables, minimizing the demand on short-term memory. During the identification task, each pseudoword was associated with a character represented on a card placed on the table. In a first learning phase, the experimenter taught the child the name of the characters by associating a gesture and a supporting phrase (a phrase containing a rhyme with the pseudoword target) to facilitate retention. This learning phase aimed to ensure that the child was able to associate each pseudoword with the corresponding character. The experimenter conducted this learning phase until perfect accuracy was achieved in the identification of the various characters, providing feedback when necessary. In the actual task, the child was instructed to select the card that matched the character mentioned in a spoken sentence and place it next to the image that corresponded to the sentence produced. For example, when given the sentence “I saw /tɔ̃tɔ̃/ on the ball”, the child would select the card labeled “/tɔ̃tɔ̃/” and place it next to the image of the ball. Given that the task’s objective was to determine whether the child correctly identifies the target pseudoword, the response was considered correct when the child selected the correct card, regardless of where they placed it.

2.3.2. Discrimination

The discrimination task consisted of the presentation of pairs of pseudowords with an inter-stimulus gap of 100 ms. A total of 63 pairs were presented in a random order, i.e., 9 blocks of 7 pairs: 5 pairs of different stimuli and 2 pairs of same stimuli. The choice of an unequal distribution between identical and different pairs was guided by the intention to enhance participants' attention and motivation while preventing fatigue from too many identical stimuli. This consideration was particularly important given that perceptual difficulties might have arisen where differences would not have been perceived. These 9 blocks aimed to assess the perceptual distance between phonetically matched nasal and oral vowels, and between phonologically matched nasal and oral vowels. Pairs of oral/oral control were also included (Table 2.6).

	ɑ̃ Pairs	N	ɛ̃ Pairs	N	ɔ̃ Pairs	N
Phonological pairing	Different :/tɑ̃tɑ̃/ – /tata/	5	Different : /tɛ̃tɛ̃/ – /tɛtɛ/	5	Different : /tɔ̃tɔ̃/ – /tɔtɔ/	5
	Same : /tɑ̃tɑ̃/ – /tɑ̃tɑ̃/	1	Same : /tɛ̃tɛ̃/ – /tɛ̃tɛ̃/	1	Same : /tɔ̃tɔ̃/ – /tɔ̃tɔ̃/	1
	Same : /tata/ – /tata/	1	Same : /tɛtɛ/ – /tɛtɛ/	1	Same : /tɔtɔ/ – /tɔtɔ/	1
Phonetic pairing	Different : /tɑ̃tɑ̃/ – /tɔtɔ/	5	Different : /tɛ̃tɛ̃/ – /tata/	5	Different : /tɔ̃tɔ̃/ – /tutu/	5
	Same : /tɑ̃tɑ̃/ – /tɑ̃tɑ̃/	1	Same : /tɛ̃tɛ̃/ - /tɛ̃tɛ̃/	1	Same : /tɔ̃tɔ̃/ – /tɔ̃tɔ̃/	1
	Same : /tɔtɔ/ – /tɔtɔ/	1	Same : /tata/ – /tata/	1	Same : /tutu/ – /tutu/	1
Oral/oral control	Different: /tata/ – /tɔtɔ/	5	Different : /tɛtɛ/ – /tata/	5	Different : /tutu/ – /tɔtɔ/	5
	Same: /tata/ – /tata/	1	Same : /tɛtɛ/ – /tɛtɛ/	1	Same: /tutu/ – /tutu/	1
	Same: /tɔtɔ/ - /tɔtɔ/	1	Same : /tata/ - /tata/	1	Same: /tɔtɔ/ - /tɔtɔ/	1

Table 2.6: Pairs of stimuli in the discrimination task.

The discrimination task consisted in a two-alternative forced-choice procedure. Children had to judge whether the stimuli within each pair were the same or different. Children's responses were collected using a computer application on a touchscreen tablet (Microsoft Surface Pro3). To facilitate the understanding of the instructions, pictograms were placed on the response areas. A brief training phase was provided to the children, during which they were asked to judge as identical or different 6 pairs of stimuli (3 identical, 3 different) from the overall protocol. Feedback was provided during this training phase to help the child correctly select what they had heard as identical or different.

2.4. Procedure

The testing involved the completion of the identification task followed by the discrimination task, in this same order for all children. For both tasks, the auditory stimuli were presented to the children in free field through loudspeakers (Bose Soundlink II) which mean sound level was controlled using a sound level meter and adjusted to 60 dB SPL (the usual threshold for perception tests), placed 1 meter away from the participants in a very quiet room.

2.5. Data analyses

The main independent variable is the auditory status of the participants (CI group vs. TH group). Another child-related variable was the chronological/auditory age (three subgroups in each group, see Table 2.2). The age of implantation was also considered by comparing children in the CI group who received their first implant early (< 10 months) or later (> 10 months). The effect of French Cued Speech (CS) exposure frequency was also studied for CI children, comparing those with occasional exposure (CI/CS-) to those with intensive exposure (CI/CS+). Regarding the task-related variables, we studied the effect of the type of vowel (oral/nasal) and the type of pair (phonologically matched oral-nasal/phonetically matched oral-nasal).

For the identification task, the dependent variable was the accuracy of the response for each target phoneme of the task (56 stimuli * 38 participants). For the discrimination task, we calculated d' scores, obtained by subtracting normalized, centered, and reduced scores of correct detection proportions (rejecting a different pair) from those of false alarms (rejecting an identical pair) (MacMillan & Creelman, 1991). Extreme responses .0 and 1 were converted to .01 and .99 to allow for the calculation of z-scores on these proportions. A d' score was calculated for each vowel pair discriminated by each participant (9 pair types * 38 participants).

Identification responses and d' discrimination scores were analyzed with linear generalized mixed models using the lme4 package (1.1-34 ; Bates et al., 2015) in the R software (R Core Team, 2022). Models were parametrized with binomial distribution for the identification task (binary dependent variable: correct/incorrect) and with Gaussian distribution for the discrimination scores (continuous dependent variable: d' scores).

Different models were created, using each child-related variable (auditory status, chronological/auditory age group, CS exposure group, implantation age group) and its interaction with task-related variables (vowel type for identification; pair type for discrimination). A random intercept effect (subject) was included in the models to control inter-subject variability. The different models were compared using the AIC criterion, to determine the best predictor of the performance. Following a procedure described in Ditges et al. (2021), statistical significance of the fixed effect of categorical variables with only two levels were determined with Z-values and p-values within the model estimates. Interaction effect and fixed effects of categorical variables with three levels were determined with Chi-squared and p-values using the ANOVA function of the Car package (Fox & Weisberg, 2018) applied on the model. Power calculations have been performed on the fixed and interaction effects obtained within the best-fitting model to quantify their reliability, using the powersim function of the SimR package (Green & MacLeod, 2016), with N=200 Monte Carlo simulations. Pairwise comparisons between the levels of the different independent variables were also conducted with the emmeans package (Lenth et al., 2023) and reported in the result Tables below. The analyses were conducted on participants' responses in the two tasks (2128 data point for identification, 342 data point for discrimination), allowing us to work with a sufficient number of statistical subjects to partition the data based on our variables of interest (TH vs. CI groups; CI exposure among the CI group) despite the small number of subjects in the constituted subgroups. The precautions taken in the selection of acoustic analyses to control for inter-subject variability (random subject effects within the models) also seem pertinent in this regard.

Finally, we calculated association measures for both of our tasks using our acoustic measurements, which were treated as an ordinal scale (7 levels for identification, corresponding on each vowel of the stimuli, and 6 levels for discrimination, corresponding on the 6 pairs). For the identification task using a dichotomous scale (correct/incorrect), we employed the rank biserial correlation coefficient (effectsize package; Ben-Shachar et al. (2020), while for the discrimination task using a metric scale (d' scores), we used the eta-squared coefficient (BioStatR package, Bertrand & Maumy-Bertrand (2009).

3. Results

In supplementary materials, all the features of the best-fitting models presented are available, namely parameter values for the levels of fixed effects variables, along with p-values and associated power analyses.

3.1. Identification

3.1.1. Correct identification scores

The percentages of correct answers in the identification task are presented in Table 2.7.

		TH	CI	Sig.
Total		97,8 (0,003)	88,5 (0,011)	<.001
Vowel	*ã*	95,6 (0,017)	79,2 (0,07)	.004
	ɔ̃	99,1 (0,005)	94,2 (0,029)	.01
	ɛ̃	99,5 (0,003)	92,6 (0,035)	.001
	a	99,5 (0,003)	90,1 (0,04)	<.001
	ɛ	99,9 (0)	98,6 (0,011)	NS
	u	100 (0)	80,1 (0,072)	NS
	o	100 (0)	98,6 (0,011)	NS
	sig.	<.001	<.001	
Vowel type	*Nasal*	98 (0,009)	88,7 (0,04)	.001
	Oral	99,8 (0,001)	92,1 (0,03)	<.001
	sig.	<.001	NS	
Chronological age	*4-6y.*	95,3 (0,03)	91,8 (0,025)	NS
	7-9y.	99,7 (0,002)	87,4 (0,045)	<.001
	10-12y.	99,8 (0,002)	88,8 (0,031)	<.001
	sig.	.008	NS	
Auditory age	*4-6y.*	95,3 (0,03)	89,2 (0,03)	.04
	7-9y.	99,7 (0,002)	89,9 (0,02)	<.001
	10-12y.	99,8 (0,002)	90,7 (0,04)	<.001
	sig.	.008	NS	

Table 2.7: Correct identification scores (marginal means and standard deviations calculated with the EMMEANS package) (in %) for TH and CI groups and the different inter- and intra-subject variables, with associated significance levels.

The best-fitting model includes the global identification score of the CI group (88.5%), which is significantly lower than that of the TH group (97.8%) (β = -2.37, SE = 0.55, z = -4.28, p < .001). Notably, 17 out of 25 children in the TH group scored 100% on this task, while the maximum score in the CI group was 98%. Across all groups, nasal vowels showed lower identification scores than oral vowels (oral: 96.4%, nasal: 92.2%; β = 0.89, SE = 0.21, z = 4.31, p < .001). Furthermore, an interaction between auditory status and vowel type was found (β =

2.27, SE = 0.66, z = 3.42, $p < .001$), with the TH group showing lower scores for nasal vowels (oral-TH: 99.6%, nasal-TH: 95.3%; β = 4.10, SE = 0.815, z = -5.036, $p < .0001$), while no significant vowel type effect was found in the CI group (oral-CI: 90.1%, nasal-CI: 86.2%; β = -0.404, SE = 0.240, z = -1.685, p = 0.09). Examining the vowels affected by these differences between our groups, we observed lower scores for the three nasal vowels /ɑ̃/ (p = .008), /ɔ̃/ (p = .01), /ɛ̃/ (p = .002), and for the oral vowel /a/ (p = .0006).

Given the different child-related variables, the best-fitting model for analyzing the identification response includes auditory status, auditory age group, and vowel type. A chronological age effect was found only in the TH group, with scores increasing significantly from ages 4-6 to 7-8 (β = 2.052, SE = 1.0366, z = 1.98, p = 0.0478) and from ages 4-6 to 10-12 (β = 3.3185, SE = 1.459, z = 2.275, p = 0.0229) for nasal vowels but not significantly for oral vowels. In the CI group, no effect of chronological age or auditory age was found for the two vowel types.

In the CI group, the best-fitting model includes a significant effect of CS exposure grouping, without an interaction with vowel type: children with more supported exposure to Cued Speech (CI/CS+) show significantly higher scores than children with occasional exposure (CI/CS-) (83% vs. 93.1%; β = 1.02, SE = 0.307, z = 3.342, $p < .001$) for both oral (β = -1.15, SE = 0.401, z = -2.857, p = .004) and nasal vowels (β = -0.904, SE = 0.388, z = -2.33, p = .01). This effect is observed for the phonemes /ɛ̃/ (p = .04) and /u/ ($p < .001$) and marginally for /ɔ̃/ ($\chi^2(1) = 2.9$; p = .08). However, the scores of the CI group with frequent Cued Speech exposure remained overall significantly lower than those of the TH group (93.1% vs. 97.8%; β = 2.05, SE = 0.788, z = -2.6, p = .009), with significant differences for the phoneme /a/ (β = -2.885, SE = 0.956, z = -3.016, p = .007) (see Figure 2.1).

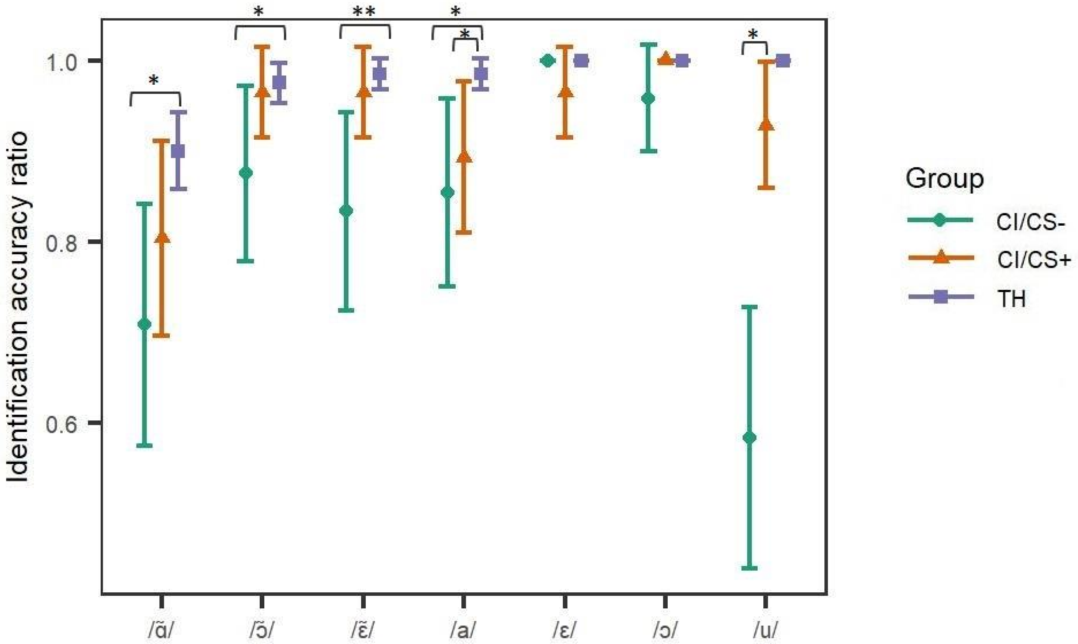

Figure 2.1: Correct identification ratio (mean and 95% CI) for each target phoneme, for the CI/CS- subgroup (dot), CI/CS+ subgroup (triangle) and TH group (square). Significant differences between groups are indicated with * (p<.05), ** (p<.005) or * (p<.001).**

The model including the effect of early implantation (without interaction with vowel type) was the second best-fitting model for the CI group (Table 2.8). The results show a marginal advantage of early cochlear implantation (< 10 months) on correct identification scores ($\beta = -0.65$, SE = 0.37, z = -1.767, p = .07). This difference was significant only in nasal vowels ($\beta = 0.904$, SE = 0.459, z = 1.992, p = .04), particularly for nasal vowels /ɑ̃/ (p = .07), with no significant differences found for oral vowels. However, the scores of early CI children remained lower than those of the TH children (92 vs. 97.5%; $\beta = 2.29$, SE = 0.883, z = 2.589, p = .009).

CI group		
Implantation	*<10m.*	92,6 (0,019)
	>10m.	86,6 (0,028)
	sig.	.07
Cued speech exposure	*Occasional*	83,5 (0,03)
	Frequent	93,4 (0,014)
	sig.	<.001

Table 2.8: CI group correct identification scores (marginal means and standard deviations) (in %) for the inter-subject variables "Implantation" and "Cued speech exposure", with associated significance levels.

3.1.2. Identification errors analysis

The confusion matrix (Table 2.9) provides information about the substitutions made by the two groups. In the TH group, the main error was substitutions of the phonemes /ɑ̃/ by /ɔ̃/ (10% of the stimuli), other substitutions being negligible (occurring with 2% or less of the total). In the CI group, the most frequent error was also confusions between /ɑ̃/ and /ɔ̃/, with a greater proportion (/ɑ̃/ → /ɔ̃/: 24%, but also conversely /ɔ̃/ → /ɑ̃/: 5.8%). Substitutions of the oral vowel /u/ was also frequent, with 15.4% of substitutions by /ɔ/ and 6.7% by /ɛ/. The other main substitution is a confusion between nasal and oral vowels of the phonetic pair /ɛ̃/-/a/: substitutions /ɛ̃/ → /a/ and /a/→ /ɛ̃/ each occurred with a proportion of 9.6%.

Stimulus		Response						
		ɑ̃	**ɔ̃**	**ɛ̃**	**a**	**ɔ**	**u**	**ɛ**
	ɑ̃	TH : 90% CI : 76%	TH : 10% CI : 22,1%	TH : / CI : 0,9%	TH : / CI : /	TH : / CI : 1%	TH : / CI: /	TH : / CI: /
	ɔ̃	TH : / CI : 5,8%	TH : 97,5% CI : 92,3%	TH : / CI : 1%	TH : / CI : /	TH : 2% CI : 1%	TH : 0,5% CI : /	TH : / CI: /
	ɛ̃	TH : / CI : /	TH : / CI : /	TH : 98,5% CI : 90,4%	TH : 1,5% CI : 9,6%	TH : / CI : /	TH : / CI : /	TH : / CI : /
	a	TH : 0,5% CI : 1,9%	TH : / CI : /	TH : 1% CI : 9,6%	TH : 98,5% CI : 87,5%	TH : / CI : /	TH : / CI : /	TH : / CI : 1%
	ɔ	TH : / CI : /	TH : / CI : 1,9%	TH : / CI : /	TH : / CI : /	TH : 100% CI : 98,1%	TH : / CI : /	TH : / CI : /
	u	TH : / CI : /	TH : / CI : 1%	TH : / CI : /	TH : / CI : /	TH : / CI : 15,4%	TH : 100% CI : 76,9%	TH : / CI : 6,7%
	ɛ	TH : / CI : /	TH : / CI : /	TH : / CI : /	TH : / CI : /	TH : / CI : 1,9%	TH : / CI : /	TH : 100% CI : 98,1%

Table 2.9: Confusion matrix for each target phoneme, for TH and CI groups.

To observe whether a phonetic/phonological proximity effect is observed, errors were classified on this substitution types: substitutions between nasal and oral vowels (or vice versa) that are phonologically related and substitutions between nasal and oral vowels (or vice versa) that are phonetically related (Table 2.10). Children in the CI group substitute more nasal vowels with phonetically related orals than TH children ($\chi^2(1) = 27.2$; $p<.001$). On the other hand, there were no significant differences of substitutions between phonologically matched oral and nasal vowels between the two groups ($\chi^2(1) = 0.638$; $p =.424$).

Substitution type	TH	CI	χ^2 ; p-value
Nasal ↔ Oral - phonological pairing	5 (0,4%)	4 (0,5%)	$\chi^2(1) = 0{,}638$; p =.424
Nasal ↔ Oral - phonetic pairing	6 (0,4%)	22 (3%)	$\chi^2(1) = 27.2$; p<.001***

Table 2.10: Number of substitutions (and % of total number of responses) for each substitution type in TH and CI groups, with associated statistical test.

3.2. Discrimination

In the discrimination task, we analyzed the d' scores, which ranged from 0 to 4.65 (see Table 2.11).

		TH	**CI**	**Sig.**
Total		4,41 (0,09)	4,12 (0,13)	.04
Pair	*/ã/-/a/*	4,41 (0,15)	4,11 (0,21)	NS
	/ɔ̃/-/ɔ/	4,34 (0,15)	3,86 (0,2)	.04
	/ɛ̃/-/ɛ/	4,56 (0,15)	4,15 (0,2)	NS
	/ɛ̃/-/a/	4,34 (0,15)	4,04 (0,2)	NS
	/ã/-/ɔ/	4,31 (0,15)	4,26 (0,21)	NS
	/ɔ̃/-/u/	4,48 (0,15)	4 (0,2)	.06
	sig.	NS	NS	
Pair type	*Phonological*	4,44 (0,1)	4,03 (0,152)	.03
	Phonetic	4,38 (0,1)	4,1 (0,152)	NS
	sig.	NS	NS	
Chronological age	*4-6y.*	4,2 (0,2)	4,18 (0,22)	NS
	7-9y.	4,47 (0,15)	3,73 (0,29)	.02
	10-12y.	4,48 (0,16)	4,15 (0,22)	NS
	sig.	NS	NS	
Auditory age	*4-6y.*	4,2 (0,2)	3,99 (0,2)	NS
	7-9y.	4,47 (0,15)	4,22 (0,25)	NS
	10-12y.	4,48 (0,16)	4 (0,29)	NS
	sig.	NS	NS	

Table 2.11: Pairwise d' scores for each group (marginal mean and standard deviation), for the different inter- and intra-subject variables, with significance level of statistical tests.

The best-fitting model included the subject random effect and the group effect, without interaction with the pair type (phonetic or phonological). Notably, the average d' score of the TH group (4.41) was significantly higher than that of the CI group (4.06) (β = 0.3427, SE = 0.1667, t = 2.055, p = .04). The two groups differed significantly only in their performance on phonological pairs (β = -0.41, SE = 0.18, t = -2.19, p = .03), while there was no significant difference for phonetic pairs (β = -0.27, SE = 0.18, t = -1.5, p = .14). We found no effects of the child-related variables, including chronological/auditory age for both groups, age of implantation and CS exposure in the CI group, regardless of the type of pairs studied (Table 2.12).

CI group		
Implantation	*<10m.*	4,06 (0,27)
	>10m.	4,07 (0,25)
	sig.	NS
Cued speech exposure	*Occasional*	3,9 (0,27)
	Frequent	4,21 (0,25)
	sig.	NS

Table 2.12: CI group d' score marginal means (and standard deviations) for the inter-subject variables "Implantation" and "Cued Speech exposure" with associated significance level.

It's noteworthy that 15 out of 25 (60%) of the typically hearing children and 4 out of 13 (30%) of the CI children achieved the maximum d' score. No effects of the child-related variables (chronological/auditory age for both groups, CS exposure, age of implantation for the CI group) were found to influence the distribution of children between those with and without this ceiling effect. Regarding the pairs investigated, 275 out of the 342 pairs studied obtained the maximum d' score. There were proportionally fewer TH children (13.3%) obtaining the maximum score for phonological pairs than CI children (33.3%) (χ^2 = 6.3; p = .012). However, this proportion was statistically equivalent for phonetic pairs (TH = 17.3%, CI = 28.2%; χ^2 = 1.8; p = .177). Among the d' values of the 67 pairs that didn't obtain the maximum scores, a differential effect of auditory status on pair type was observed. While no significant group effect was found for phonological pairs (TH = 3.04; CI = 2.77; β = 0.268, SE = 0.253, t = 1.059, p = .302), a significant difference in favor of TH children was observed for phonetic pairs (TH = 3.05; CI = 2.69; β = 0.359, SE = 0.17, t = 2.114, p = .04), as shown in Figure 2.2.

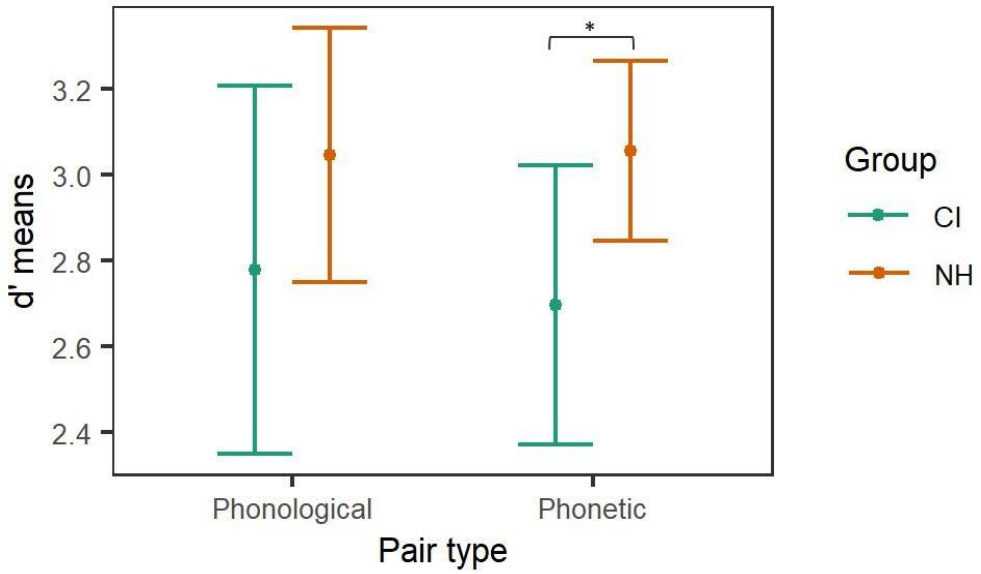

Figure 2.2: d' scores distribution (mean and 95% CL) for both groups (CI and TH) and pair type (phonological vs phonetic).

Additionally, a Pearson correlation test revealed a moderate positive correlation between the scores obtained in the discrimination and identification tasks ($r = 0.39$; $p = 0.015$).

3.3. Performance in relation to the acoustical properties of the stimuli

The measures of association between scores on perceptual tasks and various acoustic characteristics (rank biserial correlation values for identification task, eta-squared values for discrimination task) of the stimuli are available in Tables 1 and 2 in the appendices.

In the identification task, moderate to strong links are observed between the TH group performance and various categories of acoustic cues. These include formant frequency (F1, F2), bandwidth (F1, F3), amplitude (F1, F2, F3), as well as the A1-P0 and A1-P1 values. A moderate link is also found with vowel intensity. In the CI group, only weak to moderate links are observed between performance and the acoustic features of the stimuli. Links greater than 0.3 are found for formant amplitude (F1, F3) and A1-P1 values. Upon closer examination of these same associations within the CI/CS- and CI/CS+ groups, slightly different profiles emerge. Indeed, within the CI/CS- group, additional moderate links are found with the bandwidth of F1, A1-P0 values as well as the intensity and amplitude of the temporal envelope of the vowel.

In the discrimination task, children in the TH group exhibit weak correlations between their performance and within-pair differences in F2 frequency, as well as the temporal envelope of the entire pseudoword. Similarly in the CI group, there are only weak associations between performance and acoustic cues, including the bandwidth of F3, formant amplitudes (F1, F2), and A1-P1 values. A closer look at the CS- and CS+ groups reveal slightly different profiles. Specifically, in the CS+ group, there is a moderate correlation between discrimination performance and the index of temporal envelope difference computed on the first vowel (0.04), and a stronger correlation when envelope difference index is on the second vowel (0.06). In contrast, in the CS- group there are associations between discrimination scores and differences in formant frequencies (F2, F3, and the Euclidean distance F1/F2), as well as in the bandwidths of F1 and F2 and in the amplitude of F3.

4. Discussion

This research aimed to assess the perception skills of French oral and nasal vowels in children with typical hearing (TH) and children with cochlear implants (CI) aged between 5 and 11 years. The vocalic nasality in French seems to be of significant interest to investigate, given its reliance on spectral resolution skills that can indeed pose challenges for cochlear implant (CI) recipients. The investigation comprised two tasks: an identification task involving pseudowords containing oral or nasal vowels in a sentence context and a discrimination task featuring pairs of the same pseudowords. The discrimination task was designed to contrast nasal vowels with their phonological and phonetic oral counterparts, following a methodology inspired by Borel's research (2015). Our research had three main objectives: 1) to compare the performance of children with cochlear implants to that of children with typical hearing, with a specific focus on various factors that could potentially yield more favorable results (chronological/auditory age, exposure to Cued Speech, and early implantation); 2) to explore the potential impact of phonological vs. phonetic proximity between nasal and oral vowels; and 3) to investigate how different types of acoustic cues (related to spectral vs. temporal resolution) in the stimuli used in perceptual tasks might affect children's performance.

An effect of auditory status was found in both tasks, with children in the CI group showing lower scores than their TH peers in the identification and discrimination of oral and nasal vowels. In the identification task, difficulties specifically with nasal vowels were expected. However, children in the CI group also showed difficulties in identifying oral vowels, particularly for the phoneme /u/ which had the lowest identification rate after the phoneme /ɑ̃/. Although this pattern of performance was unexpected, it seems to confirm our hypothesis of processing difficulties related to the mode of sound signal transmission through the cochlear implant, making certain phonemes, including nasal vowels, more vulnerable. Due to the relative lack of spectral information transmitted by the implant, particularly in low frequencies, and lower frequency selectivity due to the distribution of electrodes in the cochlea, spectral information related to nasal sounds may be perceived with less efficiency and result in confusion for certain types of segments. The distinction between nasal and oral vowels is, as explained in section 1.1, based on subtle acoustic cues, particularly intensity ratios between low-frequency harmonics (and thus, formant bandwidth) that are modified compared to their oral counterparts. Some oral vowels, having very close F1 and F2 values in the low frequencies, such as /u/, may also be vulnerable for similar reasons. Hawks et al. (1997) demonstrated increased difficulties in identifying phonemes with synthetically widened F1 bandwidths and suggested that this widening, causing activation to spread to adjacent electrodes corresponding to the formant frequency center, may be responsible for the lower identification performance. Furthermore, CI devices may be less efficient in encoding low-frequency components of the sound signal, possibly due to a lesser coverage by the implant of the apical regions of the cochlea.

Considering this, the difficulties of CI users would not concern specific phonemes, but rather the ability to distinguish them from counterparts with comparable and better-preserved acoustic properties. This hypothesis is supported by the error patterns of the CI children in our study: while TH children make only confusions between nasal vowels, implanted children make confusions between nasal and oral vowels that are close in their oropharyngeal articulatory configuration (F1 and F2 formants), similar to the error patterns presented by Borel which motivated the decision to include “phonetic pairs” in our discrimination tasks. The error patterns observed in the identification of the /u/ phoneme also support this proposition: the /ɔ/ phoneme, which has similar spectral values, is a good candidate for substitution. Additionally, /u/ and /ɔ/ have a similar articulatory configuration, at least on the most visible dimension, namely lip rounding. The acoustic cues related to oro-pharyngeal configuration appear to have a double advantage for the cochlear implanted population: they are carried by frequency information that, as long as they are not too close (as, for example, /u/), can be relatively well perceived, and they are also accompanied by articulatory gestures that are partially visually accessible (like anterior segments : anteriority effect on phonetic production being shown in CI children by Grandon, 2016).

The fact that CI children also substitute oral vowels with close nasal vowels in terms of F1/F2 supports the idea that their difficulties do not concern a particular class of phonemes, but rather certain characteristics of the sound signal, affecting in particular nasal vowels, and therefore not allowing them to be effectively discriminated from phonetic close segments. Note that to perceive the differences between nasal and oral vowels, implanted children, in natural language situations, can rely on their perception of typical formant patterns of these vowels. They can also rely on temporal parameters, which are reported to be well transmitted by the implant. Since French nasal vowels segments are generally longer than their oral counterparts (Delattre & Monnot, 1968; Delvaux, 2012), the characteristic lengthening of these segments can be an effectively exploitable clue not degraded by the cochlear implant to distinguish nasal and oral segments. The stimuli in our study were controlled in terms of their segmental length, forcing the children to rely solely on the processing of spectral information, and thus explaining the confusions between close nasal and oral vowels on their F1-F2 configurations. Moreover, the most frequent error in the identification task within the CI group was on the nasal phoneme /ɑ̃/ confused with another nasal /ɔ̃/. This confusion can also be explained by the phonetic proximity on their F1/F2 patterns, as these two phonemes have a close oropharyngeal configuration. However, this confusion, also present in the group of hearing children, does not seem to indicate specific difficulties for children with cochlear implants.

Furthermore, in line with our hypotheses, the results of the present work contrast with the studies previously cited on one major aspect. Indeed, the performance, reaching almost 90% for the identification task and 95% for the discrimination task, are very high compared to those obtained by Bouton et al. (2012) and Borel (2015, Borel et al. 2019). These high scores can first be explained by the fact that, unlike the participants in the studies by Borel and Bouton, in which adults and children were mostly unilaterally implanted, all children in our experimental group were bilaterally implanted. The advantage of bilateral cochlear implantation has been demonstrated for speech perception, both in noise (Dunn et al., 2010; Müller et al., 2002), and in experimental situations (Anand et al., 2022; Caselli et al., 2012; Sarant et al., 2014; Zeitler et al., 2008). Furthermore, a positive impact of bilateral hearing has been demonstrated by Landsberger et al. (2018) in spectral resolution processing and by DiNino et al. (2020) in the better utilization of salient acoustic cues (cue-trading, developed below). The present results appear to support the findings of these different authors. It could be hypothesized that, in the case of nasality perception, which relies on the perception of fine spectral cues, bilateral implantation may maximize the chances for the electrodes in both ears to improve spectral resolution and cover critical frequencies for the perception of speech sounds. Sarant (2014) mentioned a benefit of bilateral implantation, particularly the “binaural redundancy effect”, which means that speech perception could be improved because the brain is presented with two opportunities to process the same signal, which is entirely congruent with this idea. This performance can also be related to the early age of implantation in our sample, with the CI children in the study mostly being implanted before the age of 2 (9 to 30 months), whereas the average age of implantation was higher in Bouton et al.’s study (22 to 42 months). Many studies document the beneficial impact of early implantation on language performance and linguistic abilities (Dettman et al., 2016; Karltorp et al., 2020; Tamati et al., 2022).

The present results support the use of CS to enhance speech sound perception: indeed, children who are exposed more intensively to CS present significantly higher performance than those who are exposed occasionally (83 vs. 93% in identification), even if the perceptual tasks here were only based on acoustic information. It should be noted that the use of CS may explain some surprising substitutions made by children in the CI group: the vowels /u/, /ɔ/ but also /ɛ/ - which are also confused with /u/ in identification tasks - are coded in the same manual position in the CS code, as the system does not anticipate confusion on these phonemes based on lipreading. It is possible that children with cochlear implants (CIs) who have been exposed to Cued Speech (CS) have internalized a representation of this manual code and may use it in cases of perceptual ambiguity. This could potentially lead to confusion between these phonemes when one of them is ambiguously perceived, and lipreading is not available to disambiguate them. Bayard et al. (2014), which have tested the McGurk effect through the presentation of stimuli in audio, visual, and audiovisual conditions with CS manual codes, supported the beneficial contribution of CS coding for visual and audiovisual speech perception and showed similar substitution patterns. Indeed, when stimuli containing incongruent auditory and visual information were presented, the use of CS manual codes led to responses consistent with the CS manual code, demonstrating integration of the CS code and its privileged use in cases of perceptual conflict. This could also partly account for confusions between /ɑ̃/ and /ɔ̃/, which are also coded in the same location in the CS system.

An effect of chronological age in children with typical hearing was found in the identification task: children aged 4 to 6 have lower scores than those aged 7 to 9 and 10 to 12. These results are in line with various studies that have shown a positive correlation between chronological age and spectral resolution performance in typically hearing children, while this link with age (chronological or auditory) was not found in the CI population (DiNino & Arenberg, 2018; Horn et al., 2017; Jahn et al., 2022). Vocalic nasality perception, involving the perception of various fine acoustic cues, can thus be particularly linked to the maturation of spectral resolution skills in typically hearing children, explaining this performance profile. Moreover, improvement within the typically hearing (TH) group starts at the age of 7, which may reflect, in addition to maturation effects, the positive impact of the introduction of written language in the school environment on perceptual performance. Indeed, it is commonly accepted that high-quality phonological representations are essential for optimal acquisition of written language, but conversely, the acquisition of written language can help stabilize or even clarify certain phonological contrasts, as demonstrated with foreign language learners (Chadee, 2013; Detey, 2005). The orthographic code, which has the advantage of being available visually, could, once correctly encoded in long-term memory, facilitate the phonological processing of certain contrasts. However, this age effect is not found in implanted children, in accordance with the literature on spectral resolution. In this population, the acoustic limitations of the transmitted signal led to perceptual adaptations that have already been discussed, which do not appear to be related to maturation effects, at least not within the age range covered by this present study.

The hypotheses elaborating on Borel's study (2015), which suggested greater difficulties for CI children in discriminating phonetically paired (vs. phonologically paired) oral and nasal vowels, were partially confirmed here, even if the discrimination scores were rather complex to study due to some ceiling effects. More than half of the TH children obtained a ceiling score on all pairs on this task, compared to one third of the CI children. The lowest scores in the CI group were for the two oral-nasal pairs containing the phoneme /ɔ̃/, the oral-nasal pair /ɛ/-/ɛ̃/ and the oral-oral pair /u/-/ɔ/. Taking all participants' results into account, the differences between groups did not reach the level of significance, most probably due to large variability in the CI group. However, by studying only the scores not reaching the ceiling we found more discrimination errors for phonetic pairs in the CI group, as did Borel, confirming the hypothesis of an increased vulnerability of these nasal/oral pairs in the implanted population and supporting the explanatory leads formulated previously. Borel (2015) reported scores below or just at chance level (26% to 42% within 4 months or less post-implantation; 43% to 69% within 12 months or more post-implantation) on a nasal vowel identification task in post-lingually deaf adults. The children in our study, who have congenital deafness and were implanted very early, exhibited superior performance. As suggested by Landsberger et al. (2018), young children developing their perceptual system around the acoustic signal transmitted by the implant may process this signal more efficiently than an adult who has developed their auditory system based on a more complete auditory signal. Indeed, babies with cochlear implants, with the support and assistance of early auditory rehabilitation during their sensitive periods of linguistic development, could develop sufficient discrimination abilities by exploiting the acoustic cues best transmitted by their cochlear implants. The implanted adults, who always had access to auditory information until the onset of deafness, would still tend to rely on spectral cues that are later absent or too imprecisely transmitted to allow them to identify certain speech units, such as nasal vowels. Brain plasticity can explain some differences between postlingually deafened adults and prelingually deafened children language outcomes: it is well established that adult brains retain some degree of plasticity, but it tends to be more limited compared to children which are highly adaptable and flexible (Ismail et al., 2017). This could also explain why the phonetic proximity of nasal/oral pairs had a lower impact on the performance of the children in this study, compared to the adult participants in Borel's study.

The analysis of potential links between performance in both tasks and the acoustic properties of the stimuli allows us to explore certain explanations for how the different groups of children process acoustic features. Firstly, let's highlight that the two tasks involve different perceptual mechanisms, which can lead to a different exploitation of perceived acoustic cues. In the case of identification, the participants must necessarily consider relevant cues to identify the target phoneme in reference to their phonological representations stored in memory. However, when discriminating between two pseudowords, the participants may not necessarily rely on their phonological representations but can solely rely on their perceptual system to identify even minor differences based on the accessible acoustic features. Furthermore, the performance between the two tasks is only moderately correlated (r=0.4), indicating that the perceptual mechanisms are not strictly identical. Indeed, the types of indices primarily associated with performance differed between the two tasks. In the identification task, children in the TH group had their performance linked to various types of acoustic cues: frequencies, bandwidths, formant amplitudes, as well as indices related to the detection of nasal poles (A1-P0, A1-P1), and more global (vowel intensity) and temporal (amplitude of the temporal envelope) indices. Conversely, children in the CI group exhibited performance associations only with formant amplitude indices and the detection of the second nasal pole (A1-P1). Different profiles emerged based on exposure to Cued Speech (CS): children in the CS- group also showed links with the utilization of F1 bandwidth, vowel intensity, and the amplitude of the temporal envelope. In discrimination, the utilization of acoustic cues was more limited for both groups of children. For children in the TH group, performance was solely associated with differences between pairs involving F2 frequency and the temporal envelope of vowels. Children in the CI group again primarily had their performance associated with differences related to formant amplitude and differences linked to the second nasal pole (A1-P1 values). Once again, differences were observed among children in the CI group based on their exposure to CS. CS- children had their performance linked to differences in F1 bandwidth, while CS+ children benefited from differences related to the temporal envelope of the vowels. Considering that the CS+ group significantly outperforms in both tasks, it is interesting to examine these different relationships between performance and acoustic features. Overall, CS- group relies on a greater number of acoustic cues (similar to the TH group), while CS+ children primarily rely on formant amplitude cues for identification and temporal envelope differences for discrimination. This strategy proves to be successful in terms of performance. This more efficient use of a more limited number of acoustic cues could be linked to the study by DiNino et al. (2020), which demonstrated that children with implants who had the best phonetic perception were also those capable of prioritizing the acoustic cues that were presumably salient to them (i.e. they were better at "cue-trading"). Regular and early practice of CS, which is recognized for leading to better phonological representations (Bouton et al., 2011; Leybaert et al., 2016; Leybaert & LaSasso, 2010; Van Bogaert et al., 2023), could therefore lead to a more efficient use of the acoustic cues that are better perceived through the implant, ultimately resulting in better speech perception performance. However, these different observations should be treated with caution. Acoustic characteristics were established a posteriori, i.e. once the construction of stimuli based on natural productions had been completed; they therefore do not vary linearly along the seven target stimuli studied. Additionally, due to the relatively high performance of our children's groups, we have limited variability in the scores, which ultimately revealed only weak to moderate links. Future studies could explore the use of natural or synthetic sound manipulation methods on these different acoustic parameters to induce more linear variations and observe their impact on phoneme perception, similar to the study about nasality perception conducted by Delvaux et al. (2012) on typically-hearing adults. This could involve more precise phonetic cue-weighting pattern comparisons about nasality perception, as seen in the work of DiNino et al. (2020).

This study presents certain limitations, the most important being the sample size of the CI group. As previously stated, the linguistic performance of children with cochlear implants varies greatly, and it would have been interesting to observe the results of our experimental tasks on a larger group with more diverse characteristics. However, the analyses conducted, considering inter-individual variability, revealed main effects (effect of auditory status, status*type of vowel interaction, effect of CS practice) with a statistical power exceeding 80% for the identification task. Effects with lower statistical power were related to age; therefore, it would be of great interest to validate the findings by better balancing the groups in terms of chronological/auditory age. In addition, the very high scores in the discrimination task led to more moderate effects. It would be interesting to replicate this type of study (discrimination of phonological vs. phonetic nasal/oral pairs) by varying the size of the stimuli. Bouton et al. (2012) and Borel (2015) used monosyllabic stimuli in their paradigms; our bisyllabic stimuli may have made the discrimination task easier. Furthermore, the average pitch of our male speaker was low, i.e., 122 Hz, and the perceptual performance of CI children may have been different with other speakers having a higher intrinsic F0. Finally, it would seem particularly interesting to include, in future studies assessing vocalic nasality contrast, non-linguistic tasks related to spectral resolution processing. Indeed, understanding to what extent these scores can explain the ease of processing vowel nasality from a developmental perspective in children with cochlear implants and typically hearing peers would help deepen our knowledge of the adaptive mechanisms by which implanted children build a phonological system based on a degraded auditory signal.

5. Conclusion

The results of this study confirm an increased difficulty for children with cochlear in identification and discrimination of speech sounds whose spectral characteristics differ in the low frequency zones and/or include close F1/F2 values, as is the case with French nasal vowels and certain oral vowels like /u/. These results, although specific to French sounds, are of great interest for understanding the specificities of the cochlear implant signal processing, and for inferring potential difficulties in other languages of the world that include sounds with these characteristics. Furthermore, it is worth noting that the performance, while remaining significantly lower than those of typically hearing peers, are relatively high (80% and above). This contrasts with previous studies that investigated nasal vowel perception in unilaterally implanted adults and children. This suggests a potential advantage of bilateral implantation for the perception of nasal/oral distinctions. Moreover, the associations between performance and the acoustic characteristics of the stimuli appear to indicate that a selective and prioritized utilization of acoustic cues (cue-trading) that are presumed to be better coded by the implant, such as the temporal envelope, can lead to improved perceptual skills. Finally, these results support the literature regarding the importance of early implantation in the development of phonological perception skills, as well as the interest in using visual support for speech perception, such as Cued Speech, to enhance better perceptual skills development in children with cochlear implants.

Chapter 3 Production of oral and nasal vowels

After studying the perceptual skills related to the vowel nasality feature, the present chapter examines the productive skills associated with nasal and oral vowels in the same children, through acoustic analyses of their speech productions as well as perceptual judgments performed on these productions. To our knowledge, this study is the first to study these skills in children with CI. The acoustic analyses aim to explore how different production strategies are used by the different groups of children for the distinction between nasal and oral vowels, as well as the impact of exposure to CS among children with CI. This study was conducted as part of the initial data collection related to the thesis, involving the same children as in Study 1 presented in the previous chapter.

The study has been submitted and, at the time of writing, has just been accepted for publication in the Journal of Speech, Language, and Hearing Research, with a reference that is, at this stage, still incomplete:

Fagniart, S., Delvaux, V., Harmegnies, B., Huberlant, A., Huet, K., Piccaluga, M., & Charlier, B. (in press). Producing nasal vowels without nasalization? Perceptual judgments and acoustic measurements of nasal/oral vowels produced by children with cochlear implants and typically hearing peers. *Journal of Speech, Language, and Hearing Research*.

The chapter presents a revised version of the manuscript, taking into consideration two rounds of reviewer feedback.

Abstract

Purpose: The objective of the present study is to investigate nasal and oral vowels production in French-speaking children with cochlear implants and children with typical hearing. Vowel nasality relies primarily on acoustic cues that may be less effectively transmitted by the implant. The study investigates how children with cochlear implants manage to produce these segments in French, a language with contrastive vowel nasalization.

Method: The children performed a task in which they repeated sentences containing a CVCV-type pseudoword, the vowel being a nasal or oral vowel from French. Thirteen children with cochlear implants (CI) and 25 children with typical hearing (TH) completed the task. Among the children with cochlear implants, the level of exposure to Cued Speech (CS) was either occasional (CS-) or intense (CS+). The productions were analyzed through perceptual judgments and acoustic measurements. Different acoustic cues related to nasality were collected: segmental durations, formant values and predicted values of nasalization. Multiple regression analyses were conducted to examine which acoustic features are associated with perceived nasality in perceptual judgments.

Results: The perceptual judgements realized on the children's speech productions indicate that children with sustained exposure to Cued Speech (CS+) exhibited the best-identified and most distinct oral/nasal productions. Acoustic measures revealed different production profiles among the groups: children in the CS+ group seem to differentiate between nasal and oral vowels by relying on segmental duration cues and variations in oropharyngeal configurations (associated with formant differences) but less through nasal resonance.

Conclusion: The study highlights 1) a benefit of sustained CS practice for CI children for the intelligibility of nasal-oral segments; 2) privileged exploitation of temporal (segmental duration) and salient acoustic cues (oropharyngeal configuration) in the CS+ group; 3) difficulties among children with CI in distinguishing nasal-oral segments through nasal resonance.

Keywords: Cochlear implant, vocalic nasality, phonetics, Cued Speech.

1. Introduction

In prelingually deaf children with cochlear implants (CI), specific characteristics in productive skills have already been observed in numerous studies. For oral vowels, children with CIs differed from typically-hearing (TH) peers in F1 and F2 frequency values and showed a tendency of vowel centralization and vowel space reduction (Liker et al., 2007; Neumeyer et al., 2010; Ryalls et al., 2003; Verhoeven et al., 2016; Yang & Xu, 2021). For consonants, studies have shown lower distinction between voiced and voiceless stops (Horga & Liker, 2006) and among the different fricative consonants (Liker et al., 2007; Mildner & Liker, 2008; Todd et al., 2011; Uchanski & Geers, 2003). In French, various investigations have shown shorter Voice Onset Time values for voiceless stops compared to individuals with typical hearing, with a significant difference for the velar /k/ (Grandon et al., 2017), as well as specificities in the distinction between fricatives /s/ and /ʃ/ (Grandon et al., 2020). In the production of vowels, differences have been observed between French-speaking children with cochlear implants (CIs) and those with typical hearing (TH) in terms of place of articulation, with rounded front vowels being more posteriorized (Grandon, 2016). Grandon has suggested that the lack of perceptual disambiguation in the visual modality for these different segments may explain these difficulties. A speech intelligibility test revealed lower performance in implanted children, despite a beneficial effect of early implantation (Grandon et al., 2020).

These difficulties can be explained by delayed or limited access to auditory input and potential limited spoken language experiences during sensitive periods of language development, which can make the development of production skills more challenging. Furthermore, since productive skills are based on complete phonological and phonetic representations, requiring auditory discrimination of all the acoustic features of spoken language (Stackhouse & Wells, 1993), the particularities observed in production could be linked to specific perceptual difficulties associated with the partial auditory input transmitted by the implant. Indeed, the sound transmitted to the auditory nerve by the implant undergoes various processing, affecting its spectral resolution, especially the temporal fine structure (TFS) cues (Moon & Hong, 2014). The resulting sound signal is then divided into frequency channels transmitted by a limited number of electrodes capable of independently transmitting electrical information to the hair cells' neurons. Various other factors related to the surgical procedure, the subject's anatomy or the etiology of deafness also impact the quality of the transmitted sound (for further explanations, see Başkent et al. (2016). Furthermore, the auditory input through the implant exhibits inaccuracies in encoding low frequencies. Indeed, depending on the depth of electrode array insertion within the cochlea, the apical regions of the basilar membrane may not have enough contact points to adequately encode low frequencies, leading to frequency compression in the lower range. The degree of coverage of the apical regions by the electrode array is also highly dependent on the subject's anatomy (Escudé et al., 2006). These degradations in the sound transmitted through the implant have been shown to have an impact on the processing of spectral resolution (Henry et al., 2005; Jahn et al., 2022; D. M. Landsberger et al., 2018) and also affect speech sounds differently depending on their acoustic characteristics. Indeed, various studies have highlighted difficulties in discriminating speech sounds where differences are conveyed by fine spectral cues or TFS cues, whereas differences conveyed by temporal envelope cues appear to be better perceived (K. Cheng & Chen, 2020; Eshaghi et al., 2022; Peng et al., 2019). This paper will specifically focus on a phonological feature carried by fine acoustic cues and therefore likely to be problematic for cochlear implant users, namely, the vowel nasality feature in French.

1.1. French nasal vowels: acoustic features and metrics

In many languages, vocalic nasality results from coarticulation, where nasal consonants precede or follow oral vowels, causing an overlap in oral and nasal gestures. While this nasalization isn't phonologically distinctive in these languages, it aids in speech perception. In French and many other languages, nasal vowels are phonologically opposed to oral vowels, and vocalic nasality constitutes a distinctive feature in the phonological system. French vocalic system consists of four nasal vowels: the open back nasal vowel /ɑ̃/, the mid-open front nasal vowel /ɛ̃/, and the mid-open rounded back nasal vowel /ɔ̃/. The phoneme /œ̃/ is increasingly rare among French speakers from different regiolects, sociolects and age groups, so this study will concentrate on the remaining three nasal vowels. In the French phonological system, the nasality feature distinguishes nasal vowels from their oral counterparts through the following phonological contrasts: /ɑ̃/ versus /ɑ/, /ɔ̃/ versus /ɔ/, and /ɛ̃/ versus /ɛ/. Specific morpho-phonological alternations in French grammar are supported by this contrast.

The adequate production of a nasal vowel requires a combination of two elements: 1) adopting an oropharyngeal configuration inherent to a specific vowel quality; 2) adding nasal resonance through the opening of the soft palate. At the suprasegmental level, a lengthening of the duration of nasal vowels has been reported (Delattre, 1954; Delattre & Monnot, 1968), and segmental lengthening has also been shown to correlate with listeners' perception of nasality (Delvaux, 2012).

From an acoustic point of view, the study of oropharyngeal configuration is typically carried out through the analysis of vowel formant frequencies, where F1 is more closely associated with the position of the tongue on the low-high dimension, F2 with the position of the tongue on the front-back dimension and F3 with lip movement (Fant, 1960). In French, the phonological system implies that each nasal vowel has an oral counterpart solely differing in nasal resonance, while maintaining similar articulatory characteristics such as place of articulation and rounding. However, chain shifts that occur in languages including French (Fagyal et al., 2006), have caused deviations from classical phonological descriptions. Empirical studies, including both perceptual (Montagu, 2007) and acoustic (Carignan, 2014) research, have demonstrated that in French, nasal vowels not only differ in nasality but also in oropharyngeal articulatory configuration from their oral counterparts with changes in the values of F1, F2, and F3.

Regarding the acoustic study of the effects of lowering the soft palate, it is more difficult to identify direct acoustic correlates that do not vary significantly according to the quality of the vowel, the phonetic environment and the speaker. Indeed, the opening of the velopharyngeal port during the production of nasal vowels results in an acoustic coupling between the nasal cavities and the main vocal tract consisting of the pharyngeal and oral cavities. The resonance system, therefore, includes three components: the pharyngeal, nasal, and oral cavities, and the resonances and anti-resonances associated with them, which makes it extremely complex and challenging to characterize (Delvaux, 2012). Several authors have identified measurable spectral changes related to vocalic nasality, like a reduction in the intensity of the first formant (Delattre, 1954; Delattre & Monnot, 1968), an overall decrease of vowel intensity and increase of formant bandwidths (House & Stevens, 1956) or the flattening of spectral peaks around F1 and F2 (Maeda, 1993). Delvaux (Delvaux, 2002; Delvaux & Metens, 2002) suggests that vowel "compactness" (operationalized as a decrease in relative intensities/increase in bandwidths of F1 and F3 with respect to F2) contributes to the perception of nasality. Chen (1995, 1997) created acoustic measures reflecting the intensity difference between the nasal poles (P0, P1) and the intensity of the first formant, thus providing a quantitative measure of spectral changes related to nasality, i.e. "A1-P0" (intensity difference between the first nasal pole and the first formant) and "A1-P1" (intensity difference between the second nasal pole and the first formant). Styler (2017) conducted a study to compare the validity of a series of acoustic measures that were assumed to be correlated with nasality in English and French. The author investigated various cues related to the appearance of nasal poles (frequencies and amplitudes of nasal poles, as well as A1-P0, A1-P1 measures) and the frequencies, amplitudes, and bandwidths of formants. The author also studied A3-P0 values which reflect the difference in amplitude between the first nasal pole and the third formant (figure 3.1). The results indicated that A1-P0, F1 bandwidth, and A3-P0 are the most robust indices of vowel nasalization, independently of the vowels studied and the language. Styler cautions about the significant inter-subject variability of the measurements, demonstrating that the acoustic manifestations of nasality were speaker- and language-specific.

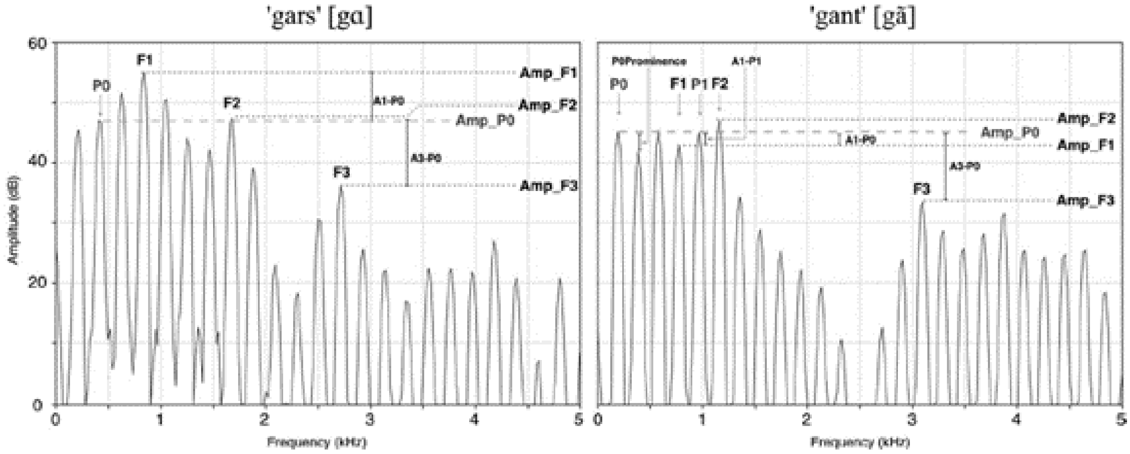

Figure 3.1: Spectra of an oral vowel /a/ (left) and a nasal vowel (right) and illustration of the methods for calculating the A1-P0, A1-P1, and A3-P0 cues. Figure from Styler, 2017.

In view of the difficulty of identifying a single metric for nasalization that is sufficiently precise and robust, Carignan proposed a new system for quantifying the time-varying degree of nasalization (Carignan, 2021). The method, called NAF (for "Nasalization from Acoustic Features"), consists, for each speaker, of a model of how nasal and oral vowels are produced, based on a series of acoustic cues validated in the literature as being associated with nasalization. When tested, the resulting system generated measurements strongly correlated with objective nasalance data collected on productions, proving its accuracy and robustness. The NAF method has since been adapted to generate speaker-specific modeling based on gradient-boosting decision tree to study the degree of vowel nasalization of Arabana speakers (Carignan et al., 2023).

It can be suspected that the three components of nasal vowel production (vowel lengthening, oropharyngeal configuration and velopharyngeal coupling) are processed differently in perception in CI recipients. Indeed, since temporal acoustic cues have been shown to be better transmitted by the implant, one can imagine that this information will be processed in a privileged way. The oropharyngeal configuration may have the perceptual advantage of being visually salient, at least for certain acoustic features (tongue height, lip-rounding) and also benefit from the somatosensory system for perception and production (Ashokumar et al., 2023; Ito et al., 2009): this productive mechanism of vowel nasality could also be favored among CI children. On the other hand, acoustic cues related to nasal resonance, which rely on precise spectral resolution, are less likely to be adequately transmitted by the implant and CI recipients do not have the opportunity to compensate by visual disambiguation or proprioceptive input. One of the main aims of the study is to examine how CI children differentially use these three components when producing nasal vowels in French.

1.2. Perception of the vowel nasality feature in French-speaking CI recipients

In French, Bouton et al. (2012) studied the ability to identify and discriminate minimal pairs containing the phonological contrasts of the French language in a group of 25 children with cochlear implants and age-matched typically-hearing peers. The results demonstrated more pronounced difficulties in perceiving the place of articulation and nasality for consonants and vowels, as these phonological distinctions rely on TFS cues, whereas voicing or manner of articulation, which depend more on temporal envelope cues, were better processed. Borel's research (Borel, 2015; Borel et al., 2019) investigated the perception skills of 82 French-speaking adults with unilateral cochlear implants. The results showed that nasal vowels were the least accurately identified segments in an identification task, with significantly lower performance compared to typically hearing adults, even after one year of implant use. The author also administered a discrimination task to a subgroup of 15 subjects in which each French nasal vowel was contrasted with "phonologically" paired oral vowels based on the classical morphophonological opposition used in French (/ɑ̃/-/a/, /ɔ̃/-ɔ/, /ɛ̃/-/ɛ/, see section 1. 2) in comparison with "phonetically" paired oral vowels (/ɑ̃/-/ɔ/, /ɔ̃/-/o/, /ɛ̃/-/a/). The so-called "phonetic" pairs consisted of each nasal vowel paired with the oral vowel closest to it from an articulatory/acoustic point of view, i.e. in terms of formant values (reflecting the oropharyngeal configuration), according to the literature (Carignan, 2014; Maeda, 1993; Montagu, 2007); these pairings also being consistent with the most common errors found in identification. Participants with CI exhibited lower scores in discriminating both types of pairs compared to those with typical hearing, but with increased difficulties in phonetic pairs. These results confirm the difficulty in perceiving the vocalic nasality feature, with challenges in using the spectral cues characteristic of nasal resonance to distinguish a nasal vowel from its closest oral counterpart (phonetic pairs).

In a previous study (Fagniart et al., 2024a), identification and discrimination abilities of pseudowords containing a target nasal or oral vowel have been tested in 13 French-speaking children with bilateral implants and 25 age-matched typically-hearing peers. The oral vowels were selected to follow Borel's (2015) phonological and phonetic nasal-oral pairings. The most frequent and specific errors in the identification and discrimination among the CI group included substitutions between nasal vowels and their close phonetic counterparts. There were also difficulties in identifying and discriminating the vowel /u/, which was interpreted as a specific challenge in accurately interpreting the formant patterns of this vowel with very close F1 and F2 values, likely due to reduced frequency selectivity. A significantly positive effect of intensive and early exposure to Cued Speech (CS) on the performance was also observed among the CI recipients. Post-hoc acoustic analyses of the administered stimuli suggested different use of acoustic cues across groups of participants. More specifically, while the performance of typically-hearing children was correlated both to acoustic variations in the fine spectral characteristics of the stimuli (frequencies, formant bandwidths and amplitudes) and to more global characteristics (intensity, temporal envelope), the best-performing CI children (those with the most experience with CS) saw their performance linked mainly to variations in the temporal envelope of the stimuli. This suggested that in perceiving French nasal vowels, children with CIs might compensate for their initial difficulties in processing fine spectral information by using acoustic cues that are better transmitted by the implant.

Considering the perceptual challenges associated with vocalic nasality perception, there is an interest in exploring how children with CIs manage to produce this contrast. This interest forms the basis for the current study.

1.3. Nasalization in the speech productions of CI recipients

Among individuals with hearing impairments, hypernasal voice quality is well-documented and has been observed through perceptual studies, acoustic analysis (Chen, 1995), and nasalance measurements (Fletcher et al., 1999). The most direct explanation for this phenomenon would be that the closure of the velopharyngeal port (VP) is not properly accomplished (absent, incomplete, or not maintained) due to inadequate auditory feedback. Lock & Seaver (1984) proposed that perceived hypernasality might not only be associated with VP opening but also with speech rate, pitch variations, or intelligibility. It is also suggested that significant posterior tongue displacement could result in abnormal resonance (described as “cul-de-sac” resonance according to Boone, 1966), which could be perceived as nasality. The introduction/restoration of auditory input through cochlear implantation allows for the normalization of the nasal/oral balance in the voices of deaf individuals, as demonstrated in various studies comparing pre- vs post-implantation performances (Nguyen et al., 2008) or with implant turned on vs off (Svirsky et al., 1998). More recently, Baudonck et al. (2015) studied nasality in 36 Flemish-speaking deaf children with cochlear implants, comparing them to 26 typically-hearing children and 25 deaf children with conventional hearing aids (HA), with an average age of 9 years. Their subjective (evaluators’ perceptual judgments) and objective (nasalance) analyses showed that both groups of deaf children (CI and HA) had a significantly more nasalized voice than their hearing peers. They reported more nasality during the production of oral phonemes than typically hearing children, while showing less nasality during the production of nasal phonemes – all segments being slightly nasalized, which is consistent with hypernasal voice quality. Among the deaf children, children with HA behaved more differently from TH children than CI recipients’ children.

To our knowledge, no study has investigated the production of the nasal contrast for French vowels in CIs users. Given the perceptual difficulties observed for this contrast in French-speaking adults and children using CIs and the hypernasality associated with impaired velopharyngeal control reported in children with CI, it seems very interesting to document how children with CI produce oral and nasal vowels in French.

1.4. Aims of the study

The present study investigates the production of nasal and oral vowels in French-speaking children with early bilateral cochlear implantation and typically hearing children, using perceptual judgments and acoustic analyses of the productions. The purpose of this dual analysis is to examine the diverse acoustic parameters of nasality to infer children’s production strategies, and to account for the perceptual outcomes associated with these production strategies among listeners. The acoustic analyses aim to objectively characterize the nasal and oral productions by studying different types of acoustic cues: 1) cues associated with oropharyngeal configuration (F1, F2, F3); 2) cues associated with velopharyngeal coupling (using the NAF method); and 3) segmental durations. Each nasal vowel is compared to its corresponding oral vowel phonologically (as per the International Phonetic Alphabet, "phonological pairs") and phonetically (based on oropharyngeal configuration similarity, "phonetic pairs" as described by Borel, 2015). The use of Cued Speech aims to create a complete and stable phonological system by providing visual cues (hand shapes and positions) to lip reading, making all the phonological contrasts of a language accessible. Its beneficial effects have been demonstrated in various perceptual aspects of language (Bouton et al., 2011; Leybaert et al., 2016; Van Bogaert et al., 2023), including the perception of vocalic nasality (Fagniart et al., 2024a). Since the productive system relies on complete phonological and phonetic representations, the positive impact of practicing CS should also be observed in production, as has been shown in articulatory and acoustic investigations (Carignan et al., 2023; Machart et al., 2021). In this perspective, the performances of children with typical hearing will be compared to those of children with CIs to evaluate the effect of auditory status in general. However, comparisons will also be conducted taking into account the level of CS exposure among CI children. This will allow us to distinguish effects related to the children's auditory condition from effects that may be modulated by the intervention for children with CIs. The present study pursues three major aims:

1. Our first objective is to document how the nasal and oral vowels produced by CI children are perceived by listeners in comparison to those produced by typically hearing peers. It can be expected that: a) listeners have lower rates of correct identification for nasal vowels produced by children with CIs and confuse them more with phonetically close oral vowels, b) nasal productions will be perceived as less nasalized, and oral productions will be perceived as more nasalized. Given that intensive CS practice has been noted as beneficial in the perception of the nasal/oral contrast, better-identified and more distinct productions in terms of nasalization could also be anticipated for vowels produced by children with extensive CS practice.
2. Secondly, we aim to acoustically characterize the productions of the three groups of children to document the production strategies they use to distinguish between nasal and oral vowels. For this purpose, the acoustic characteristics of all vowels are measured, and each nasal vowel is compared with a matched oral vowel based on phonological

contrast or phonetic similarity, following the classification proposed by Borel in 2015. Considering the literature demonstrating a differential use of acoustic cues at the perceptual level by cochlear implant recipients, it is hypothesized that children will exhibit distinct productive profiles according to their auditory status. More precisely, it is expected that children with cochlear implants, compared to children with typical hearing, differentiate between oral and nasal vowels:

a. using more segmental lengthening (as evidenced by vowel durations);
b. based more on differences in oropharyngeal configuration (as evidenced by formant values) ;
c. making less use of the cues associated with velo-pharyngeal coupling. This effect may manifest as reduced phonetic nasalization of nasal vowels and/or increased nasal resonance in oral vowels.

3. Finally, the last objective is to determine the link between the perceptual judgments obtained (i.e. nasality perceived by the judges) and the acoustic characteristics of the vowels produced, thus making it possible to link our first two objectives. More specifically, the different subject variables and the different acoustic variables will be studied to see which best predict perceived nasality in the productions of the different groups of participants.

2. Method

2.1. Participants

The study was conducted on the same participants as reported in a previous study (Fagniart et al., 2024a): a group of prelingually deafened children with bilateral cochlear implants (CI group) and a control group of children with typical hearing (TH group). The CI group consisted of 13 children (7 girls and 6 boys), aged between 5;8 years and 11;6 years (mean: 8;7 ± 2;4 years), with prelingual bilateral profound hearing loss. All children in the CI group received sequential bilateral implants and received their first implant between 9 and 30 months (mean: 13;7 ± 6 months). Their vocal audiometry curve with CI for word/pseudoword repetition ranged from 88% to 100% at 55/60dB. All of them received an oralist auditory rehabilitation, both in their rehabilitation center and in their family context. This group was divided based on their level of Cued Speech exposure: 6 of the children were exposed only occasionally (during their speech therapy sessions, with an average of three sessions per week), constituting the CI/CS- group, whereas 7 were exposed early in their development and intensively (in their family context as well as during their speech therapy sessions), constituting the CI/CS+ group. The children were recruited from the same rehabilitation center as well as a partner center in the same region, ensuring that all participants spoke the same form/dialect of French. The selection criteria for the CI group children were that they had received sequential bilateral implantation, with the first implantation before the age of 36 months. Special attention was given to CS exposure to balance the CI/CS- and CI/CS+ groups. The list of participants and their characteristics are presented in Table 3.1.

Subject	Sex	Chronological age (years ; months)	Age at first implantation (months)	Age at second implantation (months)	Cued speech exposure
CI1	M	5;11	12	23	Occasionnal
CI2	M	5;10	9	18	Early & frequent
CI3	M	6;8	10	22	Early & frequent
CI4	F	6;10	13	57	Early & frequent
CI5	M	6;11	10	15	Early & frequent
CI6	F	8;6	19	22	Occasionnal
CI7	F	8;8	12	25	Early & frequent
CI8	M	9;7	9	51	Occasionnal
CI9	F	10;8	19	N/A	Occasionnal
CI10	M	10;8	10	N/A	Occasionnal
CI11	M	10;11	10	29	Occasionnal
CI12	F	11;5	12	33	Early & frequent
CI13	F	11;6	30	43	Early & frequent

Table 3.1: Characteristics of the CI group. "N/A" indicates that the information is not available.

The TH group comprised 25 children, with 11 girls and 14 boys, ranging in age from 5 to 12 years (mean: 8; 6 ± 2;4 years). Children who had received or were currently undergoing speech therapy were not included in the recruitment process. Mann-Whitney and Krusal-Wallis tests demonstrated that the groups were equivalent in terms of chronological ages measured in months when compared on auditory status (CI vs. TH; $U(1)=0.903$; $p > .05$) as well as on CS exposure (CI/CS- vs. CI/CS+ vs. TH; $H(2) = 0.753$; $p > .05$).

This study was approved by the scientific committee of the rehabilitation where the children of CIs were recruited. Informed consent was obtained from the parents or legal guardians of all children.

2.2. Data collection

2.2.1. Task

The productions were obtained through a sentence repetition task. The sentences contained pseudowords already known to the participants because they were used in two perceptual tasks administered prior to the production task (for a description, see Fagniart et al., 2024a). The target pseudowords were in the form of C1V1C2V2 where C1=C2=/t/ and V1=V2 = /ɑ̃, ɔ̃, ɛ̃, a, ɔ, ɛ, u/. The selected oral vowels were either the phonological or the phonetic counterpart of nasal vowels, as illustrated in table 3.2. The constructed stimuli were thus /tɑ̃tɑ̃/, /tɔ̃tɔ̃/, /tɛ̃tɛ̃/, /tata/, /tɔtɔ/, /tɛtɛ/, and /tutu/.

Nasal target	Oral phonological correspondent	Oral phonetic correspondent
/ɑ̃/	/a/	/ɔ/
/ɛ̃/	/ɛ/	/a/
/ɔ̃/	/ɔ/	/u/

Table 3.2: Nasal targets and their phonological and phonetic counterparts.

2.2.2. Procedure

To make it easier for the children to process the pseudowords, they were associated with a character illustrated on a card. During an initial familiarization phase, the experimenter taught the child the names of the characters through the association of a gesture and a supporting sentence (sentence containing a rhyme with the target pseudoword) to facilitate their retention. This learning phase aimed to ensure that the child could associate each pseudoword with the corresponding character.

For the repetition task, the pseudowords were inserted into carrying sentences. Four sentences were used, with the target pseudoword in the final position (e.g. : "Near the bus, I saw /tɑ̃tɑ̃/"), resulting in a total of 28 items (4 sentences * 7 target words). During the task, the experimenter pronounced the sentence (with visible orofacial movements) while placing the card of the target pseudoword on the corresponding scene to illustrate the target sentence being produced. For example, the experimenter would take the card for /tɑ̃tɑ̃/ and place it on a picture of a lake, producing the sentence "Near the lake, I saw /tɑ̃tɑ̃/"). The child was then invited to orally reproduce the sentence. The productions were recorded using a portable Zoom H5 recorder placed at 25cm from the child.

During the assessments, some children did not complete the task for various reasons, such as fatigue. Out of the 1064 sentences expected (28 x 38 participants), 27 were missing, which accounts for 2.5% of the expected number of produced sentences. As a result, 1037 sentences were collected, totaling 2074 registered vowels. The productions of the children were manually segmented and annotated using the PRAAT software (Boersma & Weenink, 2023) to isolate the 2074 vowels.

2.3. Analysis of the speech productions

2.3.1. Perceptual judgements

All the vowels produced by the children were used in judgement tasks performed by a panel of different raters. Eight native French-speaking adults experienced in phonetic annotation of corpora were recruited as raters. The vowels produced by the 38 children were presented in isolation and distributed semi-randomly among the raters, ensuring that all productions from the same child were assigned to the same rater. To assess the inter-judge agreement, the productions of one same child of the TH group were evaluated by all the judges. Each rater had to judge from 280 to 336 productions, i.e. all the vowels produced by 5 to 6 children (from both TH and CI groups). Additionally, first author evaluated the entire sample of vowels to permit a second measure of agreement on the entire set of productions.

The raters were asked to perform two tasks: 1) a nasality judgment task for which the raters positioned each vowel production on an Osgood-type semantic differential scale ranging from 1 (oral) to 9 (nasal), and 2) a forced-choice identification task for which the raters identified each vowel production and chose from the 14 nasal and oral vowels (ɑ̃, ɛ̃, ɔ̃, a, e, ɛ, ə, i, œ, ø, o, ɔ, u, y; N=14). The same set of vowel productions was used for both tasks.

For perceived nasality, the average score across the judges and the first author rating was calculated for each vowel. For the identification task, the judge's responses were selected to be presented in the 'results' section.

The eight judges showed excellent agreement on the nasality task performed with the same participant (56 productions), as revealed by a Cronbach's alpha coefficient of 0.931. Their agreement on the forced-choice identification task of productions from the same participant is more moderate, with a Fleiss Kappa of 0.41. Agreement between the 8 raters and the first author was also measured on the entire set of production (2074 productions), with Cronbach's alpha equal to 0.801 (good agreement) for the nasality task and Cohen's kappa of 0.497 (moderate agreement) for the forced-choice identification task.

2.3.2. Acoustical analysis

Semi-automatic measurements were conducted using PRAAT scripts to collect various types of acoustic cues. Formant measurements were obtained through an automated procedure, calculating the median of formant values obtained every 5 ms within the portion of the vowel located between 25% and 75% of its total duration. Since formant values detection can be sensitive to spectrogram parameters, especially for children with high F0 values, several precautions and verifications were taken. Firstly, the formant detection parameters were adjusted for each vowel and for each child. This was done by performing a manual verification of the adequacy of the settings to correctly identify the targeted formants for each child for each phoneme. The objective was to avoid measurement errors related to significant pitch differences often found among children of various ages. After extracting the formant values based on the selected parameters, a visualization of the productions on the F1/F2 space was used to identify any aberrant values. An identification of aberrant values was also carried out to detect productions with F1, F2, or F3 values that did not fall within plus or minus three standard deviations of the subject formant mean values. All outliers were checked manually, with the spectrogram inspected to correct formant values or to exclude vowels in the case of unreadable/unclear signals (approximately 2% of the total productions). Eight productions were excluded because the formants were not clearly identifiable. The raw data were transformed into Z-scores using Lobanov's formula (1971) to neutralize the effects of speaker-specific characteristics that could be related to age and sex differences between the children, among other things.

To obtain measures of the degree of nasality in the productions, the NAF (Nasalization from Acoustic Features) method was employed (Carignan, 2021; Carignan et al., 2023). Different measures were collected through semi-automated procedures to extract a series of acoustic indices at eleven time points within the vowels. These measures included amplitude, formant bandwidth, A1-P0, A1-P1, A3-P0 (measured using the "Nasality Automeasure Praat" script by Styler, 2017), and various indices proposed by Carignan (spectral moments and nasal murmur). It is important to note that, in the approach proposed in the present methodology, the NAF method is used only to capture the acoustic effects associated with nasal resonance, while effects related to oropharyngeal configuration changes were measured separately. Consequently, certain relevant acoustic indices used in the initial method proposed by Carignan, such as formant frequency values and the first 9 Mel-frequency cepstral coefficients (MFCCs), which show moderate correlations with formant values, were not included here. Obtaining predicted nasality values using Carignan's method requires the use of supervised machine learning techniques, more specifically the gradient-boosted decision tree model. This technique requires a model to be trained on a certain proportion of data, which in turn requires a training and test sample. To obtain NAF values for the productions of all children that are comparable, a common model was constructed based on the productions of children from the TH group. Indeed, it seemed important to obtain a model calibrated on productions without specific production-level characteristics. To achieve this, we selected timepoints from the most stable part of the vowel, excluding points at 0, 10, 90, and 100% of the total vowel duration. Then, we extracted timepoints at 20, 40, 60, and 80% of the total vowel duration, solely from the productions of children in the TH group, to constitute the training sample. The testing sample was composed of timepoints at 30, 50, and 60% of the total vowel duration, within the productions of children from both the TH and CI groups. Within the training sample, productions were tagged as oral (0) or nasal (1) depending on the status of the target vowel to be produced. A gradient-boosting decision tree model (XGBoost R Package, Chen & Guestrin, 2016) with linear regression outcomes was realized. In order to optimize the model, the values of four hyperparameters (max_depth, eta, gamma, subsample) were tuned using a 5-fold cross-validation. The values of these hyperparameters that led to the lowest cross-validation error were retained for the final model. The other hyperparameters were left at their default values. The final model using the tuned hyperparameters was trained and employed to generate predictive nasality responses on the testing sample, encompassing all the children, thereby obtaining the so-called NAF values. These values numerically range between 0 and 1 and can be interpreted as a continuum on a production scale ranging from "oral" to "nasal", where productions close to 0 are not nasalized, while values close to or greater than 1 are highly nasalized. Intermediate productions close to 0.5 correspond to half-degrees between oral and nasal production.

To study the strategies used in the phonetic implementation of the phonological contrast between nasal and oral vowels, we conducted additional paired comparison analyses taking into consideration the phonetic/phonological proximity (Borel, 2015, see table 3.2) of oral-nasal pairs in French. For each child, each produced nasal vowel was paired with all its orally produced vowels that were phonetically or phonologically close, thus creating a listing of all oral/nasal pairs produced. A total of 13844 pairs were formed, allowing for comparisons of acoustic cues between each nasal-oral pair:

- Euclidean distances in the F1-F2-F3 planes (as described in Calabrino, 2006), which were calculated as follows:

For V1, a nasal vowel with coordinates (F11, F21, F31) for the three first formants in Hz, and V2, an oral vowel with coordinates (F12, F22, F32), the Euclidean distance d between these vowels points is given by

$$d_{v1v2} = \sqrt{((F1_{v2}-F1_{v1})^2+(F2_{v2}-F2_{v1})^2+(F3_{v2}-F3_{v1})^2)}$$

- Differences between segmental duration values
- Differences between NAF values

2.4. Statistical analyses

Linear generalized mixed models were used with the lme4 package (version 1.1-34; Bates et al., 2015) within the R software (R Core Team, 2022) to analyze the data. These models were configured with binomial distributions for the perceptual identification task (a binary outcome: correct/incorrect) and Gaussian distributions for all the other metric variables.

Models were constructed by including the variables related to subject characteristics (auditory status : CI vs. TH group; CS exposure among children with CIs : CI/CS- vs. CI/CS+ vs. TH), stimulus characteristics (vowel type for the speech production analysis : nasal vs oral; pair type for the nasal-oral pairwise analysis: /ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/, /ɑ̃/-/ɔ/, /ɔ̃/-/u/, ɛ̃/-/a/), and the interaction between these variables. To account for inter-subject variability, a random intercept effect for the subject was included in the model. The significance of fixed effects for categorical variables with only two levels was assessed through Z-values and associated p-values from the model estimates, following a procedure detailed in Ditges et al., (2021). Interaction effects and fixed effects of categorical variables with three levels were evaluated using Chi-squared tests and corresponding p-values, performed using the ANOVA function of the Car package (Fox & Weisberg, 2018) on the model. Pairwise comparisons between different levels of independent variables were also carried out using the emmeans package (Lenth et al., 2023). Power calculations have been performed on the fixed and interaction effects obtained within the different model to quantify their reliability, using the powersim function of the SimR package (Green & MacLeod, 2016), with N=200 Monte Carlo simulations. Effects with a calculated statistical power of less than 80% will be indicated within the results to be qualified.

Multiple regression models were also conducted to investigate which sets of acoustic cues predicted perceived nasality in perceptual judgments among nasal vowels. The regression model included the various acoustic variables (duration, F1, F2, F3, NAF values) as well as the children's chronological and auditory age. This model was tested with the different subgroups of children (TH vs CI/CS+ vs CI/CS-) to compare the impact of the different variables on the level of perceived nasality among the groups of children.

3. Results

Table 3.3 shows the mean score values for perceptual judgments as well as the mean values for the various acoustic variables studied, by vowel and by vowel type (nasal/oral) across the different groups (CI vs. TH groups; CI/CS- vs. CI/CS+ vs. TH groups), with the associated significance levels of pairwise comparison tests. Full details of the various models (estimates and standard deviations, z or t-values and associated p-values) and the associated power ratings are available in supplementary material.

		Values				Test p-values			
Measure	Vowel/vowel type	CI	CS-	CS+	TH	CI /TH	CS- /CS+	CS- /TH	CS+ /TH
Judges' nasality ratings (from 1 to 9)	ɑ̃	7.55	7.3	7.7	7.6				
	ɔ̃	7.13	6.6	7.6	7.1		*		
	ɛ̃	6.72	5.6	7.7	6.9		***	***	*
	a	2.11	2.4	1.8	2.3				
	ɛ	1.88	2	1.8	2				
	o	2.74	3	2.5	2.8				
	u	3.12	3.3	3	3.4				
	Nasal	7.13	6.5	7.7	7.2		***	*	
	Oral	2.49	2.7	2.3	2.6				

Duration (ms)	*ã*	143	142	144	126	*			
	ɔ̃	145	145	145	129	*.06*			
	ɛ̃	147	141	154	133	*.07*	*.06*		
	a	98	98	99	96				
	ɛ	102	108	98	91				
	o	109	117	103	95	*.09*			
	u	107	112	103	89	*			
	Nasal	145.8	143	148	129	*			
	Oral	104.6	109	101	93.3				
F1 (Hz)	*ã*	95	3	472	502		*		*
	ɔ̃	423	415	429	428				
	ɛ̃	507	568	455	502		***	***	***
	a	679	641	713	642		*		*
	ɛ	530	490	564	529		***	***	
	o	463	460	464	451				
	u	402	388	415	388				*
	Nasal	475	503	450	477		***		**
	Oral	519	495	539	501		**		*
F2 (Hz)	*ã*	1124	1072	1166	1251	**		**	
	ɔ̃	1181	1653	1375	1205		**		
	ɛ̃	1505	1087	1261	1424	***	***	***	
	a	1835	1729	1927	1883		*	*	
	ɛ	2477	2373	2568	2383				
	o	1327	1327	1331	1385	*.07*			
	u	1239	1252	1227	1210				
	Nasal	1271	1275	1269	1293				
	Oral	1717	1670	1757	1714				
F3 (Hz)	*ã*	2533	2732	2365	2595	**	***		***
	ɔ̃	2620	2672	2574	2453				
	ɛ̃	2863	2958	2782	2909	***			***
	a	3492	432	548	502				
	ɛ	3549	3397	3683	3603		*	*	
	o	2957	2914	2989	2832	*.06*			
	u	2668	2605	2726	2317	***	*		***
	Nasal	2671	2790	2568	2651	*	*		**
	Oral	3166	3087	3235	3061	*			*
NAF	*ã*	0.73	0.76	0.71	0.77				
	ɔ̃	0.53	0.56	0.5	0.59	*			*
	ɛ̃	0.62	0.49	0.74	0.75	***	***	***	
	a	0.43	0.4	0.45	0.3	***		**	***
	ɛ	0.14	0.13	0.15	0.11				

o	0.31	0.3	0.32	0.24	**		*
u	0.39	0.42	0.37	0.3	***	**	*
Nasal	0.63	0.61	0.65	0.70	***	**	
Oral	0.32	0.31	0.32	0.23	***	**	**

Table 3.3: Mean values of the different dependent variables (perceptual judgements and acoustic measures) by vowel and vowel types among the different groups. Significance levels for pairwise comparison tests are shown when the difference is significant at .05 (*), .001 (**) or <.001 (***). Raw values are presented for mean values but pairwise tests were realized on the z-score values.

3.1. Perceptual judgements on speech productions

3.1.1. Nasality judgement ratings

Analysis of the nasality judgment ratings showed no significant effect of auditory status (CI: 4.46, TH: 4.57; $\beta = 0.05$; SE = 0.2; t = 0.28; p=.78) nor any significant interaction effect between auditory status and vowel type ($\chi^2(1) = 0.14$; p=.71). Considering CS exposure, the CI/CS+ group exhibited higher perceived nasality ($\beta = 1.2$; SE = 0.29; t = 4.15; p < .001) and an interaction effect with vowel type ($\beta = -1.56$; SE = 0.26; t = -6.01; p < .001) with the difference being significant for nasal vowels ($\beta = -1.21$; SE = 0.29; t = -4.15; p < .001). These differences were associated with the nasal vowels /ɔ̃/ ($\beta = -1.01$; SE = 0.42; t = -2.44; p = .04) and /ɛ̃/ ($\beta = -2.19$; SE = 0.41; t = -5.29; p < .001). Comparisons between the CS-, the CS+ and the TH groups revealed that the CS- group also differed from the TH group in terms of values associated with nasal vowels ($\beta = -0.7$; SE = 0.26; t = -2.72; p = .02), and more specifically for the vowel /ɛ̃/ ($\beta = -1.36$; SE = 0.34; t = -4.02; p < .001). Additionally, the TH group displayed significantly lower values for the same vowel /ɛ̃/ compared to the CS+ group ($\beta = -0.83$; SE = 0.32; t = -2.59; p = .02).

Figure 3.2 depicts the density of nasality rating values among the TH, CI/CS-, and CI/CS+ groups. While the scores indicating less nasalized productions (1-3) were evenly distributed among the three groups, the scores indicating more nasalized productions (7-9) were less frequent for vowel produced by children of the CI/CS- group. Furthermore, there was a higher prevalence of productions judged as intermediate in terms of nasality (4-6) in the CI/CS- group.

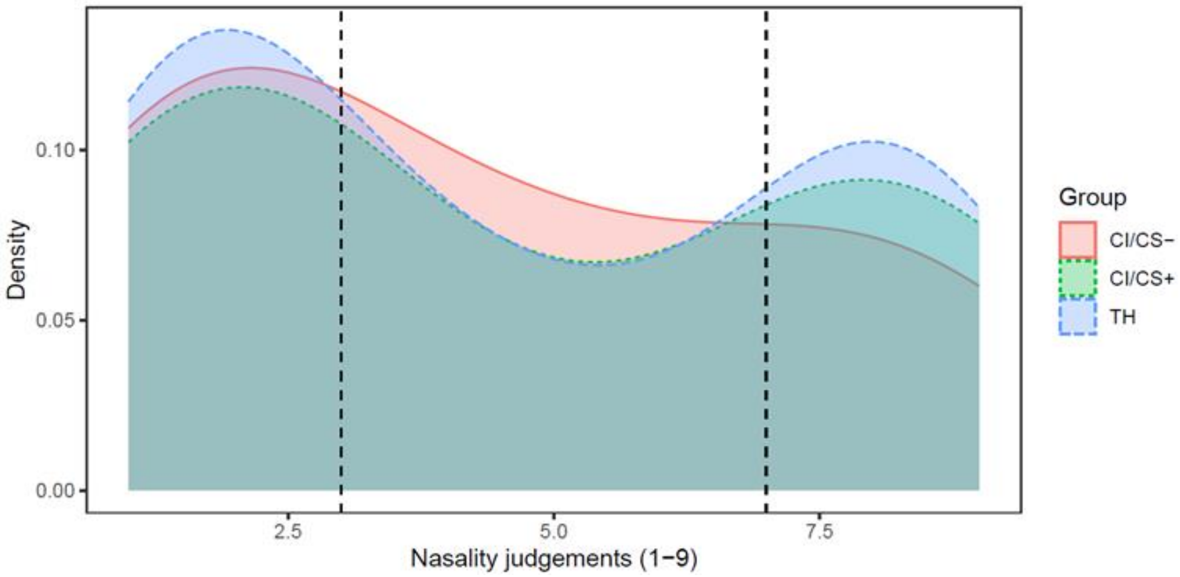

Figure 3.2: Density plot of the nasality judgement scores distribution among the CI/CS- (red and solid line), CI/CS+ (green and dashed line) and TH (blue and longdash line) groups.

3.2. Forced-choice identification scores

The percentage of productions correctly identified by the judges revealed no effect of auditory status (CI: 52.3%, TH: 45.8%; β = -0.05; SE = 0.28; z = -0.19, p = .8), but a significant interaction effect of auditory status with vowel type (β = -0.42; SE = 0.19; z = -2.14, p = .03). Indeed, the judges had higher identification accuracy for the oral vowels produced by the CI group (CI oral: 50.8%, TH oral: 39.9%; z = 1.75; p = .07), while no group effect was observed for the nasal vowels (CI nasal: 54.2%, TH nasal: 53.6%; z = 0.19; p = .8).

A significant effect of the level of exposure to Cued Speech in favor of the CS+ group was observed (CI/CS-: 45.6% - CI/CS+: 58%; β = 0.93; SE = 0.46; z = 2; p = .04) as well as an interaction effect with vowel type (β = -0.7; SE = 0.32; z = -2.15; p = .03). Nasal vowels produced by the CI/CS+ group were significantly better identified than those produced by children in the CS- group (CI/CS- nasal: 43.3% - CI/CS+ nasal: 63.6%; z = 2.1; p = .04), the difference not being significant for oral vowels (CI/CS- oral: 47.4% - CI/CS+ oral: 53.8%; z = -2.31; p = .6). The comparisons with the TH group showed no significant differences with the CS- and CS+ group. It is important to note that the various effects were only moderate (57.5 to 62%) in terms of statistical power (see supplementary material) and should therefore be interpreted with caution.

Target vowel		Identified vowel												
		ɑ̃	ɔ̃	ɛ̃	a	o	ɛ	u	ɔ	e	œ	ə	ø	y
ɑ̃	CI/CS-	48.9	25.5	2.1	14.9	2.1	/	/	4.3	/	2.1	/	/	/
	CI/CS+	62.5	17.9	17.9	1.8	/	/	/	/	/	/	/	/	/
	TH	50.5	20.6	10.8	9.8	2.6	/	/	4.1	/	1.0	0.5	/	/
ɔ̃	CI/CS-	10.9	65.2	2.2	/	8.7	/	6.5	4.3	/	/	2.2	/	/
	CI/CS+	7.1	73.2	5.4	5.4	1.8	/	1.8	/	/	1.8	1.8	1.8	/
	TH	13.0	63.7	2.1	4.1	3.6	1.0	5.7	1.6	/	1.0	3.1	0.5	0.5
ɛ̃	CI/CS-	16.7	16.7	16.7	31.3	2.1	4.2	/	/	/	6.3	4.2	2.1	/
	CI/CS+	27.3	5.5	56.4	7.3	/	/	1.8	/	/	/	1.8	/	/
	TH	19.9	9.4	46.6	13.1	3.1	1.0	1.0	2.6	/	1.0	1.0	0.5	0.5
a	CI/CS-	10.4	/	2.1	70.8	/	/	4.2	/	2.1	6.3	2.1	2.1	/
	CI/CS+	5.6	/	5.6	68.5	/	7.4	1.9	/	1.9	3.7	1.9	1.9	1.9
	TH	1.6	1.1	5.3	47.6	0.5	21.2	2.1	0.5	5.3	8.5	5.8	0.5	/
o	CI/CS-	/	22.9	2.1	2.1	33.3	2.1	6.3	14.6	6.3	8.3	2.1	/	/
	CI/CS+	1.8	10.5	/	1.8	21.1	1.8	17.5	24.6	/	/	10.5	10.5	/
	TH	4.1	10.2	1.0	1.0	16.3	3.1	8.7	14.3	3.6	13.3	9.2	11.2	4.1
ɛ	CI/CS-	/	6.3	4.2	2.1	/	41.7	/	/	27.1	14.6	2.1	/	2.1
	CI/CS+	1.8	/	/	/	/	78.2	/	/	20.0	/	/	/	/
	TH	1.6	2.1	0.5	2.1	/	60.6	2.1	/	21.2	3.1	4.7	1.0	0.5
u	CI/CS-	/	29.2	4.2	/	8.3	/	43.8	6.3	/	/	/	2.1	4.2
	CI/CS+	1.9	17.0	1.9	/	11.3	/	47.2	11.3	/	/	3.8	3.8	1.9
	TH	1.6	22.9	3.6	1.6	7.8	1.0	35.4	6.8	3.1	2.1	5.7	3.1	4.2

Table 3.4: Identification matrix of the judge's identification percentages among the CS/CS-, CI/CS+ and TH groups. In diagonal and bold typology are represented correctly identified productions.

Table 3.4 shows the identification matrix of the judges' identification responses across the three groups of children (TH, CI/CS+, CI/CS-), allowing to document typical substitutions. Overall, the most frequent substitutions concerned substitutions between oral vowels (CI/CS-: 18.6%, CI/CS+: 19.9%, TH: 26.4%). These substitutions often involved differences in vowel height, such as between /o/-/ɔ/ or /e/-/ɛ/,/ɛ/-/œ/, /e/-/œ/. Substitutions among nasal vowels were also observed in equal proportions across all three groups (CS-: 10.5%, CS+: 10.5%, TH: 10.8%) and mainly consist of /ɑ̃/-/ɛ̃/ and /ɑ̃/-/ɔ̃/ substitutions. Notably, there was a substantial proportion of substitutions between a nasal vowel and its phonetic counterpart which were pronounced by children of the CS- group (15.3%) and to a lesser extent of the TH group (10.5%), followed by the CS+ group (6.5%). These substitutions primarily involve phonemes such as (/ɛ̃/-/a/, /ɑ̃/-/ɔ/, /ɑ̃/-/o/, /ɔ̃/-/o/, /ɔ̃/-/u/). Substitutions between a nasal vowel and its phonological oral counterpart were 5.4% for stimuli from the CS- group (/ɔ̃/-/ɔ/, /ɑ̃/-/a/) and negligible in the other groups.

3.3. Acoustic measurements on speech productions

3.3.1. Segmental duration values

A significant effect of auditory status was observed on the segmental durations, with the CI group displaying overall longer segmental values (CI: 122, TH: 108; $\beta = -16.25$; $SE = 7.77$; $t = -2.09$; $p = .04$ – moderate effect size of 52%), with an interaction with vowel type at the borderline of significance ($\chi^2(1) = 3.12$; $p = .07$). Figure 3.3 shows indeed that the difference in duration between nasal and oral vowels was greater in the productions of CI children. Pairwise analyses confirmed the group effect among nasal productions (CI: 146, TH: 129; $z = 2.09$; $p = .04$) but not among oral productions (CI: 105, TH: 93; $z = 1.46$; $p = .15$).

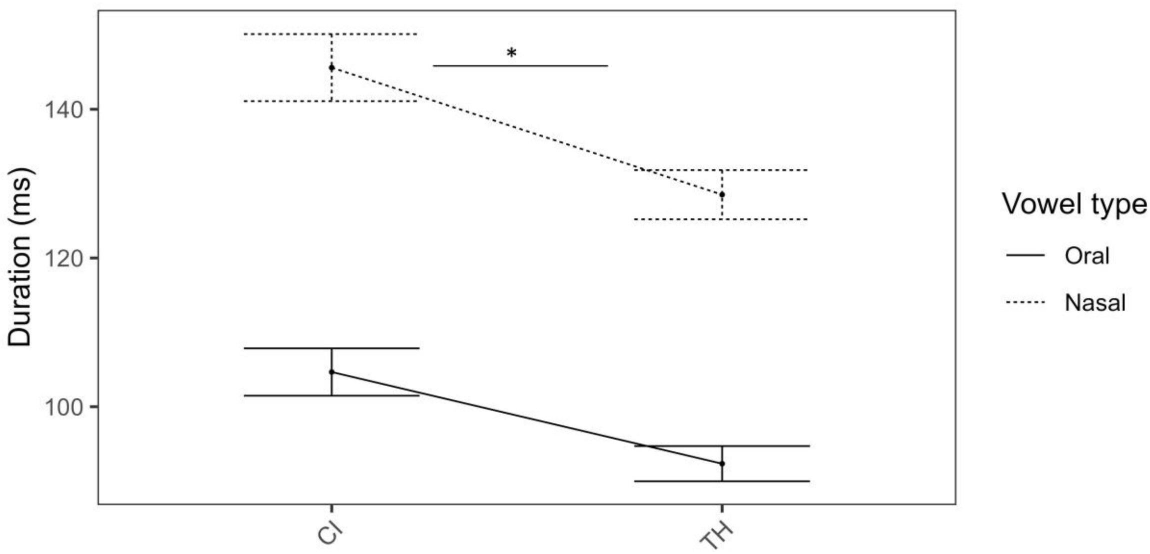

Figure 3.3: Mean and standard deviation (error bars) of duration values (ms) among the CI and TH group for the oral and nasal target vowels. Significance levels for pairwise comparison tests are shown when the difference is significant at .05 (*), .001 (**) or <.001 (***).

There was no effect of CS exposure level, but an interaction effect between this variable and vowel type is retrieved ($\chi^2(2) = 10.28$; $p = .005$). This interaction effect was related to the CI/CS+ group showing the largest difference between nasal and oral pairs in terms of vowel duration.

3.3.2. Formant values

The F1 values didn't show an effect of auditory status ($\beta = 0.06$; $SE = 0.07$; $t = -0.91$; $p = .36$) or an interaction with vowel type. Figure 3.4 displays the values of F1, F2, and F3 for the nasal and oral vowels in the TH, CS-, and CS+ groups. Considering CS exposure, an interaction effect was observed for F1 values between the three groups of participants and vowel type ($\chi^2(2) = 26.88$; $p < .001$). Indeed, F1 values were significantly lower in the CI/CS+ group for nasal vowels and higher for oral vowels compared to the other two groups. This effect was significant for nasal vowels /ɑ̃/ and /ɛ̃/, as well as oral vowels /a/ and /u/. Vowel /ɛ/ exhibited significantly lower values in the CI/CS- group than in the other two groups. For F2 values, there was no significant effect of the auditory status or CS exposure variables. However, there were significantly lower values for /ɛ̃/ and /a/ in the CI/CS- group compared to the other two groups and for /ɑ̃/ compared to the TH group. F2 was higher for /ɔ̃/ in the CI/CS- group than in the CI/CS+ group. For F3 values, an effect of auditory status was observed, with values being higher in the TH group ($\beta = 0.15$; $SE = 0.06$; $t = 2.31$; $p = .02$ – with a moderate effect size of 63%), along with an interaction with vowel type ($\chi^2(2) = 8.99$; $p = .002$). In fact, while for nasal vowels, the CI group showed higher values ($\chi^2(2) = -2.31$; $p = .02$ – with a moderate effect size of 68.5%), children in this group exhibited lower values for oral vowels ($\chi^2(2) = 1.91$; $p = .05$). Considering CS exposure, an interaction effect between groups and vowel types was identified ($\chi^2(2) = 18.27$; $p < .001$). The CS+ group had lower F3 values for nasal vowels than the other two groups. This effect was significant for nasal vowels /ɑ̃/ and /ɛ̃/ (only compared with the TH group). For oral vowels, lower values were observed for /ɛ/ in the CS- group compared to the others, and higher values for /u/ in the CS+ group.

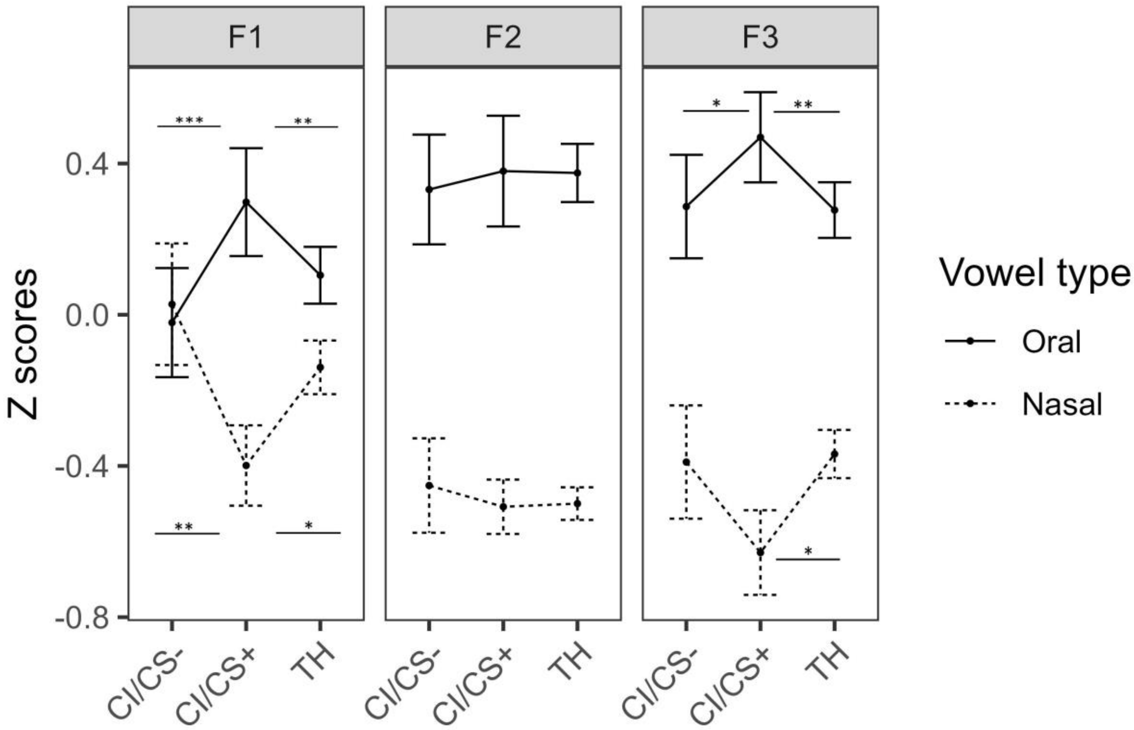

Figure 3.4: Mean and standard deviation (error bars) of F1, F2 and F3 frequency values converted in z-scores among the CI and TH groups for the oral and nasal target vowels. Significance levels for pairwise comparison tests are shown when the difference is significant at .05 (*), .001 (**) or <.001 (***).

In summary, as displayed in Figure 3.4, children from the CS+ group differed from other children in that they distinguish nasal vowels more from oral vowels in terms of F1 and F3 frequencies.

3.3.3. VP-coupling effect: predicted degree of nasalization (NAF)

A significant effect of auditory status was observed on the predicted degree of nasalization from acoustic features (NAF values) ($\beta = 0.07$; SE = 0.02; t =3.53; $p < .001$), along with a significant interaction effect between auditory status and vowel type ($\chi^2(1) = 63.28$; $p < .001$). With reference to children with CIs, TH children had higher values for nasal vowels (CI : 0.63, TH : 0.70 ; $\beta = -0.07$; SE = 0.02 ; t = -3.53 ; $p < .001$) and lower values for oral vowels (CI : 0.32, TH : 0.23 ; $\beta = 0.08$; SE = 0.02 ; t = 4.53; $p < .001$), leading to greater distinction between nasal and oral vowels in terms of nasal resonance. This effect was retrieved for the nasal vowels /ɔ̃/ and /ɛ̃/ as well as for the oral vowel /a/, /o/ and /u/.

An interaction effect between CS exposure grouping and vowel type ($\chi^2(2) = 64.52$; p<.001) was observed. Indeed, TH children had higher NAF values for the nasal vowels than CI/CS- group (β = -0.09; t =-3.53; p < .001), but lower values for the oral vowels than the CI/CS+ group (β = 0.09; t =3.9; p = .001) and CI/CS- group (β = 0.08; t =3.2; p = .006). Figure 3.5 shows predicted degree of nasalization (NAF) for all vowels according to the three groups of participants. Among nasals, the CS+ group had NAF scores equivalent to the TH group for /ɛ̃/ and higher than CI/CS- group. TH group showed significantly lower NAF values for the oral vowel /a/ than CI/CS- and CI/CS+ group, lower than CI/CS+ group for /o/ and lower than CI/CS- for /u/.

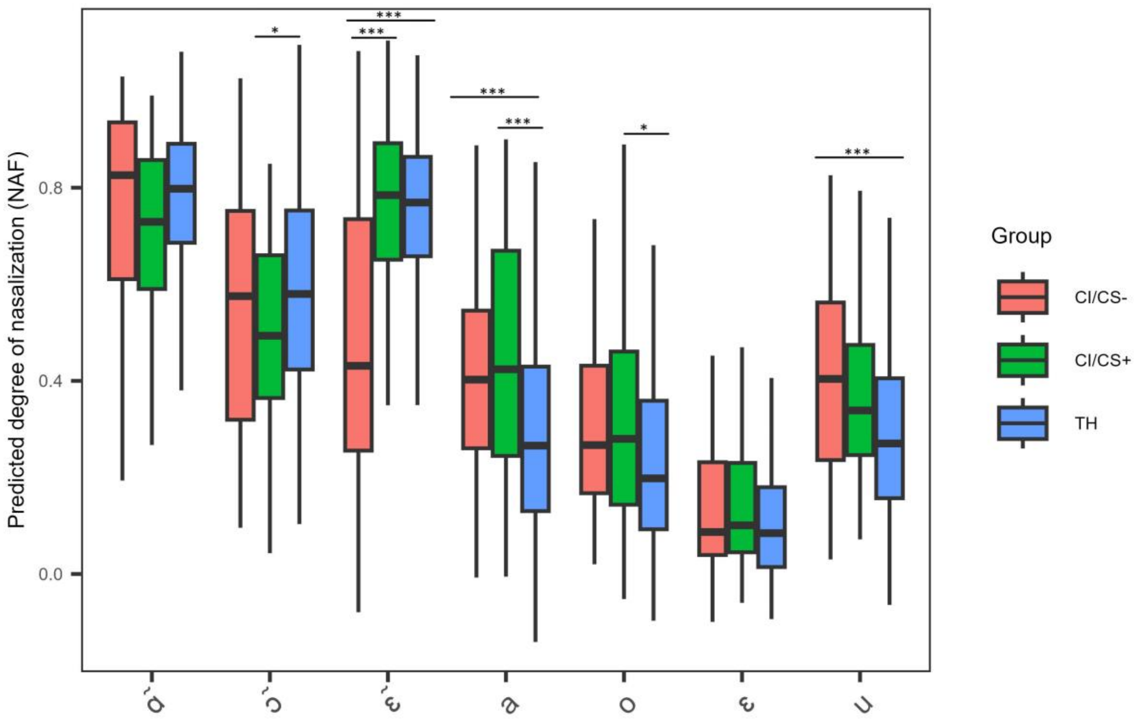

Figure 3.5: Boxplots of NAF values among the CI and TH group for the target vowels. Significance levels for pairwise comparison tests are shown when the difference is significant at .05 (*), .001 (**) or <.001 (***).

3.3.4. Nasal-oral pairwise comparisons

To investigate the production strategies by which children distinguish between nasal and oral vowels, the vowels were compared in pairs, establishing pairs between each nasal vowel and its phonological and phonetic oral counterparts. An interaction effect was observed for the duration values between auditory status and pair type, i.e. one of the six pairs (Table 3.2) (χ^2 (5) = 73.78; p <.001), indicating larger differences in duration within the /ɑ̃/-/a/ (β = 15.42; z=2.68; p=.007) and /ɛ̃/-/a/ (β = 13.1; z=2.28; p=.02) pairs among CI group children. With regard to Euclidean distances in F1/F2/F3 space, an interaction effect between hearing status and pair type was also observed (χ^2(5) = 61.02; p <.001). The pairwise analyses show no significant auditory status group difference for any tested pairs. For NAF values, an auditory status effect with higher NAF value differences in the TH group was found (β = 0.17; SE = 0.04 ; z = 3.6 ; p < .001) as well as an interaction effect between auditory status and pair type ($\chi^2(5) = 102.46$; p < .001), this effect being retrieved for all pairs with greater extent for /ɑ̃-o/ and /ɛ̃-ɛ/.

Figure 3.6 illustrates the pairwise comparisons across the TH, CI/CS+, and CI/CS- groups for the three types of acoustic cues. For duration values, an interaction effect was observed between the CS exposure grouping and pair type ($\chi^2(10) = 104.47$; p < .001). Indeed, differences in duration are greater in the CS+ group than in the TH group for the /ɑ̃/-/a/ (β = 16.28; z = 2.29; p = .05) and /ɛ̃/-/a/ (β = 19.37; z = 2.72; p = .01) pairs. Also, CS+ children had significantly higher values than CS- children for /ɛ̃/-/ɛ/ pairs. Regarding Euclidean distances in the F1/F2/F3 space, an interaction effect was also observed between the CS exposure grouping and pair type (χ^2 (10) = 316.25; p < .001). This effect was significantly observed within the pairs /ɑ̃/-/a/ and /ɑ̃/-/o/. For the pairs /ɛ̃/-/ɛ/ and /ɛ̃/-/a/, we found again more within-pair differences in duration in the CS+ group, followed by the TH group, then the CS- group. For the differences in terms of NAF values, an effect of the CS exposure grouping was found ($\chi^2(10) = 468.57$; p < .001), with greater differences between the oral and nasal members of the pairs for children in the TH group compared to CS- (β = -0.17 ; z= -2.78; p = .01) and CS+ (β = -0.14 ; z = -2.47; p = .03) groups. Looking more closely at the nasal-oral pairs (as shown in figure 3.6), CI/CS+ group had significantly lower NAF value differences than TH group for /ɑ̃-a/, /ɑ̃-o/, /ɔ̃-o/ and /ɔ̃-u/ while CI/CS- group had significantly lower values than TH and CI/CS+ group for /ɛ̃-a/ and /ɛ̃-ɛ/.

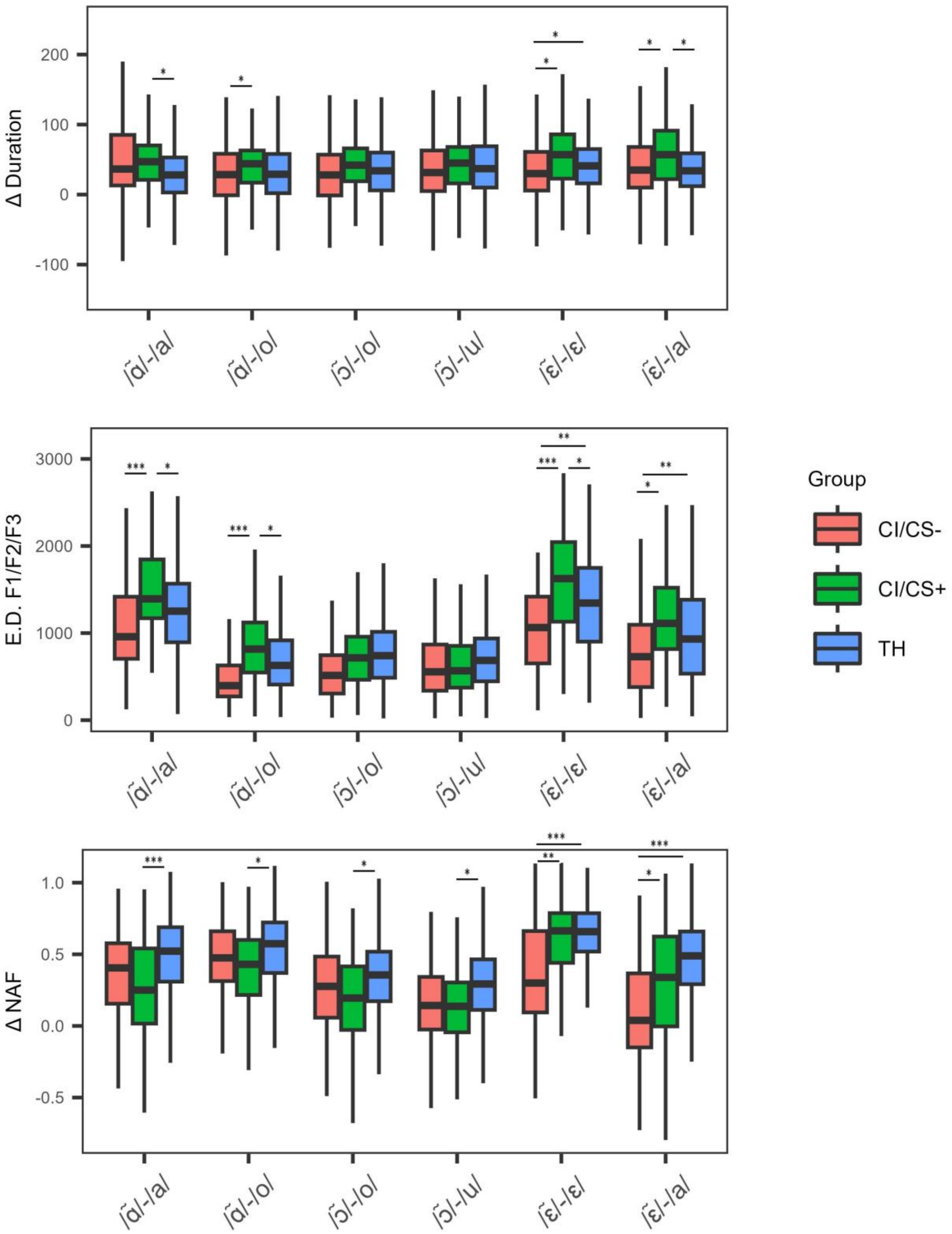

Figure 3.6: Boxplots of delta durations, F1/F2/F3 Euclidean distances and delta NAF values among the CI and TH groups for the nasal-oral pairings. Significance levels for pairwise comparison tests are shown when the difference is significant at .05 (*), .001 (**) or <.001 (***).

3.3.5. Relation between perceived nasality and acoustical data

Multiple regression modeling was performed in three groups of participants, respectively, in order to uncover the speaker-related and task-related variables as well as the acoustic cues which better predict perceived nasality among nasal vowels as measured by degree of nasality ratings (table 3.5). Duration values were significantly associated with perceived nasality in the three groups, with the greatest impact in the CI/CS- group. Similarly, the predictive values of the formant values were similar across the three groups, with a significant impact of F2 and F3 values on the perceived nasality values. NAF values, on the other hand, showed a different trend, being significantly associated predictors of perceived nasality in the CI/CS- and TH groups, but not in the CI/CS+ group. Thus, the acoustic cues associated with VP-coupling were not significantly associated with perceived nasality in the CI/CS+ model.

	CS-	**CS+**	**TH**
Intercept	3,99***	5,74***	6,2***
Chronological age	0,033	0,012	-0,005*
Auditory age	-0,03	-0,003	NA
Duration	1,05***	0,51***	0,31***
F1	-0,23	0,05	-0,14
F2	-0,59*	-0,95***	0,36*
F3	-0,36*	0,43*	-0,41***
NAF	1,91*	0,67	1,97***
Model R-squared	0,38***	0,2***	0,08***

Table 3.5: Results of the multiple regression modeling across the CS-, CS+ and TH groups for nasal vowels predicting perceived nasality in perceptual judgements.

4. Discussion

The purpose of this study was to investigate the production of nasal and oral vowels in children with early bilateral cochlear implantation compared to typically-hearing peers. Among children with CI, Cued Speech (CS) exposure has been considered as a potential explaining factor. This investigation was carried out by means of perceptual evaluations of the recorded productions, as well as their acoustic analysis based on a variety of acoustic cues reflecting the key elements of oral and nasal vowel production in French. These cues included segmental duration, formant frequencies associated with oropharyngeal configuration, and nasal resonance predicting values associated with velopharyngeal coupling. The nasal vs. oral vowels were acoustically compared based on phonologically and phonetically matched nasal-oral pairs, similar to comparisons used in previous perceptual tasks (Fagniart et al., 2024a), and previously described by Borel (2015).

4.1. Perceptual judgments of productions

The first objective of the study was to examine the accuracy of the vowel productions as evaluated through perceptual judgments. Judges listened to the nasal and oral vowels produced by the children and performed a task of identifying the vowel and quantifying the degree of perceived nasality. Contrary to what was expected, no effect of auditory status was observed on the percentage of vowel identification. It was only by considering the exposure of children with cochlear implants to CS (CS- group: late and occasional exposure vs. CS+ group: early and sustained exposure), that differences between groups emerged. Indeed, the CI/CS+ group had the most accurately identified productions. The performance of the typically hearing children closely followed that of the CI/CS+ group, with the CI/CS- group having the least well-identified productions. These results highlight the positive impact of CS exposure on the intelligibility of vowel productions, reinforcing findings in the literature on the benefits of CS practice (Bouton et al., 2011; Leybaert et al., 2016, 2016; Machart et al., 2021; Van Bogaert et al., 2023). It may have been surprising to find that the CI/CS+ group had productions judged to be more intelligible than those of the TH group. The CI/CS+ children, being more accustomed to testing situations and paying greater attention to their pronunciation through the practice of CS, may have demonstrated better performance than the typically hearing children, who are less focused on their production skills. It should be noted that the identification rates of the three groups of children are relatively low, which can be explained by the non-ecological presentation context (isolated vowel, unimodal audio presentation) and the fact that listeners had to choose from the entire set of French phonemes (N=14), leading to more uncertainty. Furthermore, most errors concerning oral vowels involved confusions in terms of tongue height (/o/-/ɔ/; /e/-/ɛ/) in roughly equal proportions in all three groups. This result can be explained by their close acoustic proximity (associated with French mid vowels specific phonological patterns: Fougeron & Smith, 1993; Nguyen & Fagyal, 2008), which is usually disambiguated in ecological situations through lip-reading and lexical context. However, we found errors in the identification task consisting in confusions between nasal and oral vowels more frequently in the CI/CS- group, primarily between phonetically similar nasal and oral vowels (/ɛ̃/-/a/, /ɔ̃/-/u/-/o/), but also within phonologically matched pairs (/ɑ̃/-/a/). It is worth noting that this type of error was also found in a smaller proportion for the vowels produced by the typically hearing group, demonstrating the proximity of these productions in typically developing children. Substitutions between oral and nasal vowels were the least frequent for productions from the CS+ group, further supporting the contribution of CS in building robust phonetic and phonological representations, at least in the case of the vowel nasality feature. It is also noteworthy that /ɔ̃/ was the most accurately identified nasal vowel, but that oral vowels /o/ and /u/ were frequently misidentified as /ɔ̃/. In this sense, it appears that the judges tended to favor the nasal vowel /ɔ̃/ in cases of uncertainty, leading to very good identification scores for this vowel when it was actually presented. In terms of perceived degree of nasality, the CI/CS+ children produced the most appropriately polarized vowels in terms of absence of nasalization for oral vowels and presence of nasalization for nasal vowels. Performance on the vowels of typically hearing children is close to that of the CI/CS+ group. Perceived nasality was significantly higher for the oral vowels pronounced by the CS- group, and more of their productions were judged to be intermediate in terms of nasalization, indicating that their productions were difficult overall for the judges to classify in terms of nasality.

4.2. Acoustic analyses of productions

Our second objective was to acoustically characterize the children's productions, specifically focusing on three categories of acoustic cues: segmental durations, formant values, which are mainly associated with oropharyngeal configuration, and NAF values reflecting degree of phonetic nasalization. Regarding duration cues, it had been hypothesized that children with cochlear implants (CI) would exhibit a more significant differentiation between nasal and oral vowels through segmental lengthening, which was confirmed by the results. Indeed, children in the CI group had overall longer segmental durations, especially for nasal vowels. Furthermore, among the CI children, it was observed that those with sustained CS practice marked the nasal-oral difference even more in terms of segmental durations. Segmental lengthening is a feature that has been shown to be strongly related to the perception of nasality in vowels (Delattre & Monnot, 1968; Delvaux, 2021) making it an effective production strategy, which seems to be confirmed by the fact the vowels produced by the CI/CS+ group were better perceived overall. Given that temporal cues are well-coded by the cochlear implant, it is probably not surprising that segmental duration is favored by children with cochlear implants to implement the oral-nasal contrast in their vowel productions. In a previous study (Fagniart et al., 2024a), we found that the CI children who achieved the best performance in the perception of nasal and oral vowels – in fact, the very same CI/CS+ children as in the current study – , were those whose perceptual performance was (moderately) correlated with temporal envelope variation in the stimuli. It would therefore seem that sustained practice of CS is associated with better use of temporal cues, both in speech perception and speech production.

As for the characterization of the productions in terms of formant patterns, a more pronounced differentiation between oral and nasal vowels on this parameter was expected in children with cochlear implants (CI), perhaps even more so in children with sustained exposure to CS. A simple auditory status effect (CI vs. TH) was only found for the values of F3. However, the CI/CS+ group exhibited significantly higher F1 and F3 values for nasal vowels, and significantly lower F1 and F3 values for oral vowels compared to the other groups. Children with extensive exposure to CS thus seem to differentiate nasal and oral vowels more in terms of oropharyngeal configuration. Indeed, lower F1 and F3 values would be associated respectively with lower opening and greater rounding of the lips for the nasal vowel. Conversely, oral vowels, produced with higher F1 and F3 values, seem to have been produced with greater tongue height and less rounding. Nasal vowels therefore seem to have been better distinguished from their oral counterparts through visually accessible acoustic cues to production in the CS+ group. This hypothesis seems convincing since exposure to CS, which emphasizes speech perception through lip-reading and manual cues, can make oropharyngeal configurations more salient in perception and, in this case, during the production of vocalic segments. The study of comparisons between nasal and oral pairs in Euclidean distances on F1-F2-F3 planes confirms a better distinction in terms of oropharyngeal configuration in the CS+ group, particularly for pairs including the nasal /ɑ̃/ (/ɑ̃/-/a/ and /ɑ̃/-/o/) and /ɛ̃/ (/ɛ̃/-/ɛ/ and /ɛ̃/-/a/). The benefit of CS in phonetic production had already been highlighted by Machart (Machart, 2021) in the differentiation of plosive and fricative consonants in French, assessed through acoustic and articulatory analyses. These new findings extend this observation to the differentiation of vowel segments based on nasality. In contrast, children in the CS- group consistently showed the lowest distinction values; hence, it can be suspected that in the absence of a system aiding in the perception of phonological features like CS, children with CI are vulnerable in distinguishing between nasal and oral vowel segments, even on more visually salient features. Pairs including the nasal /ɔ̃/ show the lowest values across all groups, signifying perceptual proximity at the oropharyngeal level, with even significantly lower scores for the /ɔ̃/-/o/ pair in the CS- group. This proximity may explain the judges' frequent responses for /ɔ̃/ when identifying productions: the nasal vowel /ɔ̃/, very close to its /o/ and /u/ counterparts, was a preferred response by listeners.

To characterize the distinction between nasal and oral vowels in terms of phonetic nasalization, various acoustic cues related to nasal resonance were collected and modeled per speaker to obtain predicted nasality values using the method proposed by Carignan (Carignan, 2021; Carignan et al., 2023). Given the limitations of cochlear implants in precisely transmitting spectral resolution (Jahn et al., 2022), these acoustic cues associated with velopharyngeal port opening may be more challenging for children with cochlear implants (CI) than for their typically hearing peers. Results of the present study provided evidence in favor of this hypothesis: children in the CI group (CS+ and CS-) produced nasal segments with less phonetic nasality and oral segments with more phonetic nasality, which results in less distinction between these two types of vowels. This finding is consistent with the observations of Baudonck (Baudonck et al., 2015) who found that Dutch-speaking implanted children showed more nasalance in oral vowels and less nasalance in nasal vowels in sentence production. Baudonck et al. (2015) suggested possible difficulties in the control of the velopharyngeal port movements to explain the lesser differentiation between oral and nasalized segments. In the case of French, it is also possible that this reduced marking of vowel nasality through nasal resonance cues reflects a reduced perceptual detection of vowel nasal resonance, which is also congruent with results in the identification and discrimination of oral and nasal vowels in a previous study (Fagniart et al., 2024a). If the partially complete auditory input transmitted by the cochlear implant does not allow children to perceive the oral/nasal distinction in terms of phonetic nasalization with sufficient precision, their discrimination abilities and, subsequently, their production abilities of this distinctive feature may be impaired. This can be manifested as both less oralization of oral vowels and less nasalization of nasal vowels. However, these difficulties seem to be effectively compensated by using more salient temporal cues (segmental duration) or visual cues (tongue/jaw height or lip-rounding) to distinguish these segments when children are exposed to methods that make all phonological features accessible, such as the CS, as the previous results have demonstrated.

Indeed, early and intensive exposure to CS appears to compensate for the perceptual difficulties associated with cochlear implants. A prior study demonstrated the positive impact of CS in the identification and discrimination of nasal and oral vowels (Fagniart et al., 2024a). In the present production study, the oral and nasal vowels produced by children with sustained CS exposure were identified most accurately, and their degree of nasality was judged to be more congruent with their phonological status. CS, through the addition of manual cues to lip-reading, aims to enable complete differentiation of all the sounds in the language using visual cues. The auditory input from the cochlear implant, combined with intensive use of CS, seems to have allowed children in the CS+ group to better distinguish nasal and oral vocalic segments, both in perception and production. The specific production strategies observed in children in the CS+ group appear to indicate a preference for using temporal cues as well as acoustic cues related to oropharyngeal configuration cues, which may reflect the better utilization of these cues observed in perception. It has already been shown in the literature that children with cochlear implants who perform best in speech perception are also those who make better use of acoustic cues (cue-weighting, DiNino et al., 2020).

Many studies have already highlighted a visual bias in the perception of spoken language among both adult and child cochlear implant users through paradigms such as McGurk (Rouger et al., 2008, 2012), especially among users of CS (Bayard et al., 2014). In the "Weight Fuzzy Logical Model of Perception" (WFLMP; Schwartz, 2010) the weighting of visual and auditory modalities in speech perception can depend on the individual and the task. In the present case, children in the CI/CS+ group could be considered as giving more weight to visual information to distinguish between nasal and oral vowels. Targeting the visual cues associated with the oropharyngeal configuration of French nasal vowels can be an effective perceptual strategy to compensate for the difficulties in processing spectral resolution related to simple nasal resonance. Children in the CI/CS+ group who employ this strategy have the most polarized scores in perceptual judgments (low perceived degree of nasalization for oral vowels and high perceived degree of nasalization for nasal vowels), even in the absence of large variations in nasal resonance. On the other hand, children in the CS- group may turn out to be less efficient in processing visual information and may rely more on the auditory modality, even if it is impaired. In view of the limitations of the implant in sound processing, this strategy may not be sufficient to perceive and produce the nasal-oral distinction as accurately. Note that the presentation of the stimuli (presentation through repetition by the experimenter, with access to lip reading) might have reinforced the preferential use of the visual modality in CS+ children. It would be interesting to know whether similar results were obtained with an audio-only presentation: perhaps the advantage demonstrated by the children in the CS+ group would be less pronounced.

4.3. Link between perceptual judgments and acoustic analyses

Our final objective was to study, in the different groups of participants, the link between the degree of nasality perceived by the judges among nasal vowels and the acoustic characteristics of the productions. Multiple regression analyses confirmed that a different set of acoustic characteristics was related to the percept of nasality depending on the group of participants, with the CI/CS+ group once again standing out from the other groups. While the modelling of the CI/CS+ group only includes formant values and segmental duration cues as predictors of perceived nasality, the CS- and TH groups also include cues associated with velopharyngeal port opening. These analyses confirm the discussion points mentioned earlier: the CS+ group had productions that were judged better than those of the CS- group in both perceptual tasks. However, the CI/CS+ group productions differed from those of the TH group, especially regarding the acoustic cues associated with nasal resonance. This multiple regression analysis confirmed that there was no link between the perceived degree of nasality and nasal resonance in the CI/CS+ group. These children manage to convey correctly the oral-nasal phonological contrast for vowels, even in the absence of a clear distinction in terms of nasal resonance in their productions, through effective use of other relevant acoustic cues. Conversely, children in the CS- group, with the least well-identified productions and the fuzziest nasal quality, appear to use velopharyngeal coupling more similarly to the TH group in the implementation of nasal contrast. This does not seem to be effective in achieving adequate perceptual correlates of the oral-nasal distinction in French vowels.

4.4. Contributions and limitations of the study

This study has provided valuable initial results on the productive skills of children with cochlear implants compared to typically hearing peers in the case of the vowel nasality contrast, setting the stage for further work on this topic. Some methodological aspects of the present study are worth noting in that perspective. First, the number of participants, although in line with most of the relevant literature, remains of moderate proportion. It seems of great interest to continue research on this topic and validate the observations with larger samples of participant. Second, the experimental task used in the present study to collect the productions consisted of a repetition task. The target pseudowords had been presented beforehand, and their memorization had been trained through a learning phase. It is therefore difficult to know whether the children relied on their memory representations of the target pseudowords, or whether they relied solely on their verbal short-term memory to repeat the productions. It would be interesting to replicate this study by contrasting the data collection method between a simple repetition and a naming task, in order to assess the phonological stability of the productions (Grandon & Vilain, 2020). Finally, it would also be appropriate to investigate the productive skills of post-lingually deaf adults with CIs in the case of French oral and nasal vowels, to find out whether prior auditory experience enables better control of nasal resonance cues.

5. Conclusion

The results of the study highlight: 1) a benefit of sustained CS practice in children with CI for the intelligibility of their oral and nasal vowels; 2) a privileged exploitation of the acoustic characteristics associated with visually salient cues in the CS+ group, i.e. acoustic cues dependent on the oropharyngeal configuration of the vowel (in particular, tongue height and lip rounding) ; 3) difficulties among children with CI in distinguishing nasal-oral vowels on the basis of phonetic nasalization (i.e. nasal resonance resulting from velo-pharyngeal coupling). These findings shed light on the importance of understanding the mechanisms through which children with cochlear implants can compensate for the acoustic limitations of their implants to support the development of effective articulatory strategies to implement the phonological contrasts of their language.

Chapter 4 Production of fricative consonants

The present chapter aims to study the production skills of children with CI in the case of another type of segment: fricative consonants. Indeed, the distinction between the different places of articulation for fricative consonants relies on high-frequency spectral information, which may be imprecisely coded through a CI. Various investigations in the literature have shown increased difficulties in accurately producing these segments (Mildner & Liker, 2008; Reidy et al., 2017; Todd et al., 2011; Warner-Czyz & Davis, 2008), including among French-speaking children (Grandon & Vilain, 2020). This study explores the subject in greater depth by examining, in addition to cues related to distinctions between places of articulation, those associated with the degree and quality of frication. Regarding the variables associated with the participants, the effects of chronological/auditory age, expo-sure to CS, and the timing of implantation are evaluated. This study was conducted as part of the second data collection and includes 23 children with CI and 47 children with typical hearing.

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Production of fricative consonants in French-speaking children with cochlear implants and typical hearing: acoustic and phonological analyses.

Sophie Fagniart[1], *Brigitte Charlier*[2,3], *Véronique Delvaux*[1,2,4], *Bernard Harmegnies*[1,2], *Anne Huberlant*[3], *Myriam Piccaluga*[1] *& Kathy Huet*[1]

[1]Language Sciences and Metrology Unit, UMONS, Mons, Belgium
[2] ULB - Université Libre de Bruxelles, Brussels, Belgium
[3]Functional Rehabilitation Center « Comprendre et Parler », Brussels, Belgium
[4]Fund for Scientific Research (F.R.S.–FNRS), Belgium
sophie.fagniart@umons.ac.be

Abstract

The following study investigates fricative consonant production skills in 23 children with cochlear implants (CI group) and 47 children with typical hearing (TH group), matched by chronological and auditory age. The voiceless (/f/,/s/,/ʃ/) and voiced (/v/,/z/,/ʒ/) fricative consonants of French were studied from children's productions to a picture naming task. The results showed lower percentages of correct fricatives as well as fricativization and stopping errors in the CI group. Acoustic analyses showed productions differing between our two groups, with lower mid-frequency amplitude peak values for the /f,s,z/ phonemes, higher amplitude in the low-frequency bands and lower high-frequency energy in the CI group. Furthermore, links between phonological performance and acoustic productions is demonstrated: higher spectral values distinction are associated with a higher percentage of correct phonological production and fewer stopping/fricativization errors.

Index Terms: cochlear implants, fricative consonants, phonetics, phonology.

1. Introduction

1.1. Speech sound production and cochlear implants

Cochlear implantation, by providing partial auditory input, can significantly improve oral language intelligibility. However, numerous studies on speech sound production have shown specificities compared to age-matched peers with typical hearing, especially for fricative segments among consonants. Warner-Czyz & Davis (2008) studied consonant and vowel inventories and error patterns in a longitudinal study of young children with implants, compared with peers with typical hearing. Although production improved with age and CI use, consonants remained less accurate than vowels overall, with specific difficulties for children with CIs for fricative consonants. The authors suggest that the degraded auditory input provided by the implant may diminish the distinctiveness of fricative segments, carried by very high frequency ranges of lower intensity than vowels and less well encoded by the implant. This auditory-based theory is supported by various acoustic studies of fricative segment production. For example, studies showed less distinction in the /s/-/ʃ/ contrast (Mildner & Liker, 2008; Reidy et al., 2017; Todd et al., 2011), but also specificities in /f/-/s/ in French (Grandon & Vilain, 2020) as well as overall lower spectral values (Yang & Xu, 2021) in children with CI compared with typical-hearing peers of the same chronological and/or auditory age. However, it is noteworthy that some authors reach different conclusions regarding the developmental profile of children with CI. For example, Kim & Chin (2008) observed error patterns in children with CI in terms of fortition errors (stopping of fricatives, devoicing) or lenition errors (fricativization of stops, voicing) typology in connection with Jakobson's markedness theory (Jakobson, 1968). The prevalence observed in the study of fortition-type errors in children's development is consistent with the early phonological development stages of typically hearing children, suggesting a chronologically delayed acquisition profile but not specific to these children. Faes & Gillis (2016) reach similar conclusions, noting that performance in the production of fricative consonants is delayed when comparing children with CI to typically hearing (TH) children of the same chronological age, but not when they are matched by lexicon size. Considering these various studies and perspectives, it seems interesting to study the link between phonological production (with subjective analysis of the level of phonological accuracy and error patterns) and objective acoustic analysis of fricative segments among CI users. This constitutes the main objective of the present study.

1.2. Acoustics of fricative consonants

Fricative consonants are produced by the partial obstruction of airflow by the articulators, resulting in the generation of a noise source filtered by the shape of the vocal tract. Frication noise covers thereby a wide frequency and dynamic range that can vary over time (Shadle et al., 2023). The acoustic study of fricative segments is conventionally conducted through the measurement of spectral moments (Forrest et al., 1988). However, the values of spectral moments can vary depending on recording conditions and are highly dependent on analysis parameters (Shadle et al., 2023). Additionally, these values are often challenging to interpret in terms of effects related to the source or the filter (Koenig et al., 2013), prompting the development of new measurement techniques. Various studies have validated the relevance of using spectral peak measured within mid-frequency range, as well as measurements of amplitude ratios (AmpDiff/AmpRange) and acoustic energy (levelD) between low/mid and mid/high-frequency ranges (Jesus & Shadle, 2002; Koenig et al., 2013; Shadle et al., 2023). These measures allow the differentiation of various places of articulation for fricative consonants and distinguish voiced from voiceless fricatives. Voiced segments exhibit lower amplitudes in mid and high-frequency ranges compared to their voiceless counterparts (Shadle et al., 2023). These measurements are performed within spectra generated by the Multitaper Method (MTPS) (Blacklock, 2004), which averages a series of periodograms obtained through the collection of mutually orthogonal windows (tapers). The MTPS method is recognized for its reduced errors and higher temporal precision (Sfakianaki et al., 2024).

1.3. Aims of the study

This study pursues three main objectives: a) documenting production performance in terms of accuracy in the phonological production of fricatives within words, as well as error patterns ; b) characterizing productions using recently developed acoustic indices aimed at assessing the articulatory and aerodynamic characteristics of fricatives (spectral peak, levelD, and ampDiff/ampRange) based on their place of articulation and voicing mode within our groups; c) studying potential links between phonological performance profiles and characteristic errors of children's groups with their production profiles in terms of acoustics.

2. Method

2.1. Participants

The TH group consists of 47 French-speaking children with typical hearing, with an average age of 56±13m., who do not exhibit any learning delays or auditory disorders. The CI group is composed of 23 French-speaking children (mean age: 67±15m.) with congenital bilateral profound deafness, fitted with bilateral implants. Both groups were divided into three/four chronological age groups: 2;6-3;6 years (only for TH group), 3;7-4;6 years, 4;7-5;6 years, and 5;6-7 years (see table 4.1). For children in the CI group, auditory age groups were also formed, considering their age from the time of their first implantation.

Group	Chronological age subgroups	Auditory age subgroups
CI	3;7-4 (7), 4;7-5;6 (6), 5;7-7y. (11)	3;7-4 (12), 4;7-5;6 (7), 5;7-7y. (5)
TH	2;6-3;6 y. (9), 3;7-4 (10), 4;7-5;6 (17), 5;7-7y. (11)	N/A (typical hearing)

Table 4.1: Description of participants in each group and age subgroups

2.2. Task

The children's productions were collected through an image naming task, for which target words were selected to encompass all the phonemes of French in initial, medial, and final positions. Additionally, these words were chosen for their frequency and low age of acquisition to facilitate their production among young children. The target words containing fricative consonants total 25 fricative phonemes per child. The productions related to target words, such as demonstratives like "ça" (/sa/- (this) or "ça c'est" - /sa sɛ/ (this is) containing a fricative phoneme, have been retained for analysis, totaling 1947 target fricative phonemes. The children's productions were recorded using a portable Zoom H5 recorder.

2.3. Data processing and statistical analysis

All audio files underwent annotation by an initial examiner and were subsequently reviewed and corrected, if necessary, by the first author using Phon 3.1 software (Hedlung & Rose, 2020). Inter-annotator agreement was high (> 90%). These annotations facilitated the extraction of the Percentage of Correct Phonemes (PCP), Correct Fricatives (PCF), and the identification of various types of production errors made by the children when there were discrepancies between the annotation and the target segment. Different types of errors involving fricatives were identified, including changes in manner of articulation (fricativization: stop to fricative; stopping: fricative to stop), changes in place of articulation, or substitutions between voiced and voiceless segments. The annotations were then exported to PRAAT (Boersma & Weenink, 2023) textgrid, with manual correction of the phoneme alignments. A script for automatic extraction of acoustic measures was subsequently employed for the analysis of the produced fricatives. The script extracts various measures at three temporal points: the beginning, middle, and end of the phoneme. For each temporal point, a multitaper power spectra (MTPS) (Blacklock, 2004) using 8 tapers was generated. Three acoustic measures were then collected from the generated spectra: spectral peak, levelD, and ampDiff for each target sibilant /s,z,ʃ,ʒ/ or ampRange for each target non-sibilant /f-v/. These measures require defining ranges for low, mid, and high frequencies within the spectrum. Given the absence of references for young children, we established these ranges through a meticulous analysis of the spectra, employing trial-and-error to identify parameters that most accurately represent our data. Finally, we adopted the values proposed by Shadle for adult females (Shadle et al., 2023) with slight changes. Notably, we adjusted the maximum threshold for the mid-frequency range in the detection of spectral peaks for /s, z/ by elevating it to 10000 instead of 8000 and to 8000 instead of 4000 for /ʃ, ʒ/. The spectral peak was obtained by extracting the frequency of the amplitude peak in the mid frequencies, levelD was obtained calculating the difference in acoustic power between mid and high frequencies, and ampDiff the amplitude difference between low and mid frequencies. Precise definitions of these measures are provided in (Shadle et al., 2023). Linear generalized mixed models were conducted using the lme4 package (version 1.1-34) (Bates et al., 2015) in the R software (R Core Team, 2022), employing Gaussian regression for all metric variables derived from the acoustic analysis of all produced segments. For phonological analysis, percentages of correct phonemes (total, nasal vowels, fricatives, and stop consonants), as well as percentages of various types of errors observed, were calculated per subject to enable group comparisons. The models incorporated subject-related characteristics (auditory status, chronological/auditory age group), stimulus characteristics (fricative time point, fricative identity, place of articulation and voicing mode), and the interaction between these variables. To control inter-subject variability, a random intercept effect for the subject was included in the models. Significance testing for fixed effects were assessed using Chi-squared tests and corresponding p-values, conducted through the ANOVA function of the Car package (Fox & Weisberg, 2018) on the model. Pairwise comparisons between different levels of independent variables were also conducted using the emmeans package (Lenth et al., 2023).

3. Results

3.1. Phonological analysis

The CI group exhibits significantly lower percentages of correct phonemes (PCP) compared to the TH group (75% vs. 91.1%; $\chi^2(1) = 30.024$; $p < 0.001$), as well as lower percentages of correct fricatives (PCF) (72.1% vs. 90.4%; $\chi2(1) = 35.857$; $p < 0.001$). An effect of chronological age is observed in the typically hearing group (TH) for both PCC ($\chi^2(3)=8.1$; $p=.04$) and PFC scores ($\chi^2(3)=13.7$; $p=.003$), with scores increasing with age. In contrast, no effect of chronological or auditory age groups is observed in the cochlear implant group (CI). The most frequent errors in both groups involve substitutions of voiced fricatives (CI : 11% – TH: 8.7% ; $\chi^2(1)=1.2$; $p>.05$) and substitutions between the phonemes /s/ and /ʃ/ (CI: 7.27%, TH: 6.1% ; $\chi^2(1)=0.74$; $p>.05$). Fricativization errors were found in the CI group, which were minimal or absent in the TH group (CI: 10% , TH: 0.8% ; $\chi^2(1)= 94.9$; $p<.001$) as well as stopping errors (CI: 4.2% , TH: 0.7% ; $\chi2(1)= 29.8$; $p<.001$) and voicing errors (CI: 4.8% , TH: 1.8% ; $\chi^2(1)= 29.8$; $p<.001$). A significant chronological age effect was observed for /s/-/ʃ/ substitutions in both the TH ($\chi^2(3)= 26.6$; $p<.001$) and CI groups ($\chi^2(2)= 18.2$; $p<.001$), but only for the TH group for devoicing ($\chi^2(3)= 8.6$; $p=.03$) – older age groups showed fewer occurrences of these errors. Concerning specific errors in the CI group, an auditory (not chronological) age group effect was observed for fricativization errors ($\chi^2(2)= 29.2$; $p<.001$), but not for stopping and voicing errors.

3.2. Acoustic analysis

Figure 4.1 displays the values of various spectral measures and amplitudes within the TH and CI groups at three temporal points for the six target fricatives.

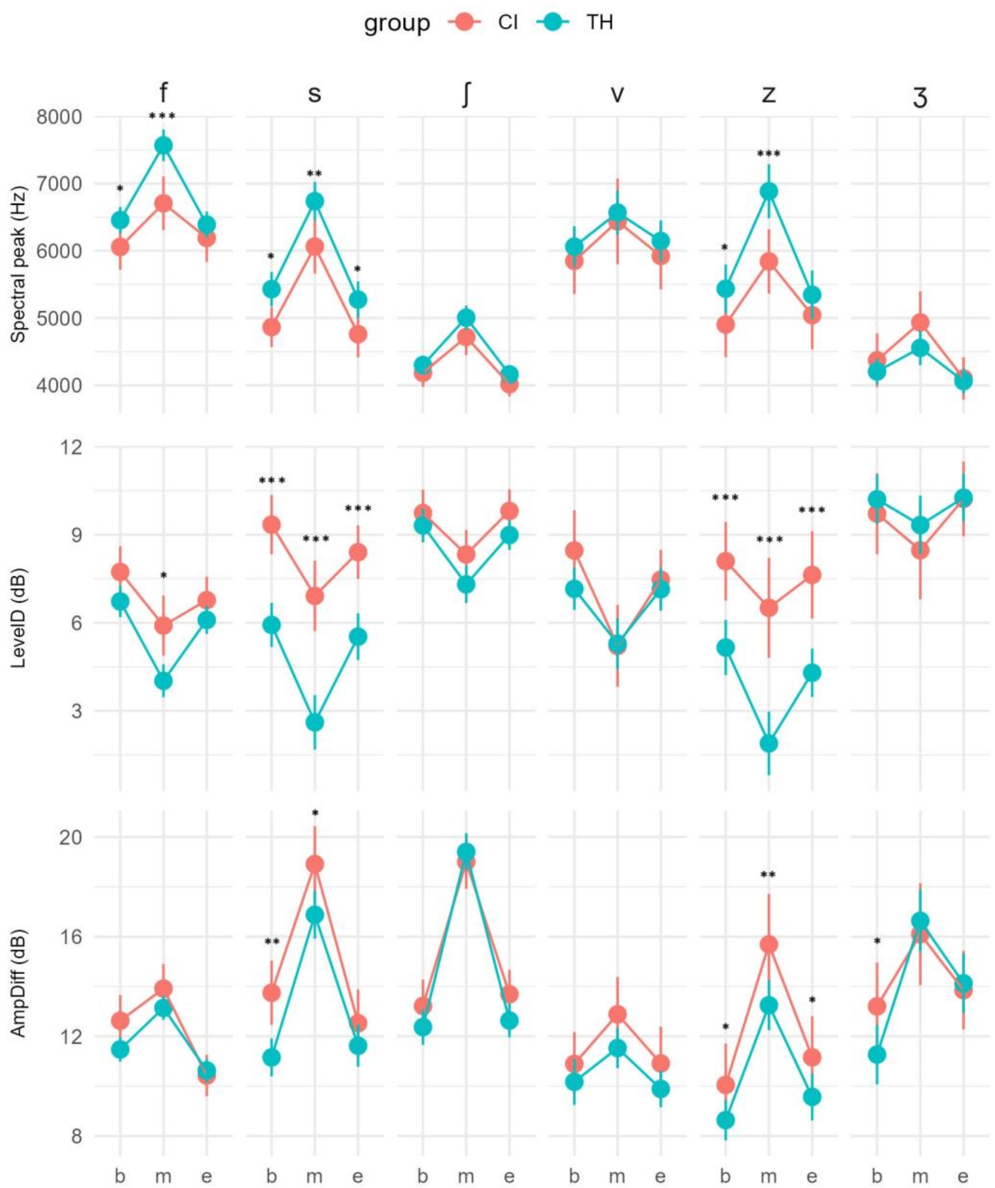

Figure 4.1: Mean and confidence interval of the spectral peak (top graphs), levelD (middle) and AmpDiff (down) values for the TH (blue) and CI (red) groups for the 6 target fricatives at three segmental temporal points (b= beginning ; m = middle ; e = end of the fricative)

Concerning spectral peak values, a group effect was observed, indicating lower spectral peak values in the CI group ($\chi^2(1) = 9.4$; $p = 0.002$). Additionally, there was a temporal point effect, showing higher values at the midpoint ($\chi^2(2) = 337.5$; $p < 0.001$). A significant interaction effect was found between group and phoneme type ($\chi^2(5) = 23.9$; $p < 0.001$), with group differences noted for the phonemes /f/, /s/, and /z/, and a group*temporal point interaction ($\chi^2(10) = 40.4$; $p < 0.001$) revealing a greater increase at the midpoint for the TH group. In the TH group, an effect of chronological age was observed ($\chi^2(3) = 11.6$; $p = 0.008$), with spectral peak values decreasing with age. An age*phoneme interaction effect

($\chi^2(15) = 66.4$; $p < 0.001$) revealed higher decreases for /f/ and /s/, resulting in improved distinction of articulation places among voiceless fricatives /f, s, ʃ/. Among voiced fricatives, /v/ and /z/ did not show distinction in terms of spectral peak values. In the CI group, no effect of chronological age was found. Instead, an interaction effect of auditory age group*phoneme ($\chi^2(10) = 22.6$; $p = 0.01$) was observed, with greater spectral peak value distinction in the older auditory age group for the voiceless /f, s, ʃ/ but not for the voiced /z, ʒ/, which were not distinguished.

Regarding the levelD values, a significant group effect is observed, with significantly higher values in the CI group ($\chi^2(1) = 5.6$; $p =.01$), along with a temporal point effect, indicating decreasing values at the midpoint ($\chi2(2) = 231.7$; $p < 0.001$). A group*phoneme interaction effect ($\chi^2(5) = 98.6$; $p < 0.001$) is also noted, with values significantly higher for /f, s, and /z/ in the CI group. An interaction effect between chronological age group is observed in the CI group, demonstrating greater distinction between the three places of articulation for the voiceless /f, s, ʃ/ and the voiced /v, z, ʒ/, with values increasing with posteriority in the older group. A chronological age group effect is also noted in the TH group ($\chi^2(3) = 14$; $p = 0.002$), with significantly lower values in the younger children age group, and an interaction between age group and phoneme, with this decrease being significant for /s, ʃ, z/. A marginal voicing*group interaction ($\chi^2(1) = 2.8$; $p = 0.09$) was also found, with significant difference between voiced and voiceless levelD values in the TH group, but not in the CI group. A place of articulation*group interaction ($\chi^2(1) = 89$; $p < .001$) reveals that, in the TH group, /s,z/ has the lowest values, followed by /f,v/, and then /ʃ-ʒ/, whereas in the CI group, the order is /f,v/ < /s,z/ < /ʃ-ʒ/.

AmpDiff values are marginally lower in TH group ($\chi^2(1) = 3.5$; $p =.06$) and a group*phoneme interaction effect is observed ($\chi^2(1) = 14.1$; $p =.01$) with significantly lower values for /s,z/ in the TH group. A time point effect is retrieved, with higher values for the midpoint ($\chi^2(2) = 687.7$; $p <.001$). In the TH group, a chronological age group effect was observed ($\chi^2(3) = 16.6$; $p < .001$) with significantly lower values in the younger age group and an age group*phoneme interaction ($\chi^2(15) = 69.9$; $p < .001$), indicating an increasing distinction between the three places of articulation for voiceless and voiced fricatives in the older group. In the CI group, both chronological and auditory age group effects were found, leading to an increased distinction between the voiceless /f/ and /s, ʃ/ and the voiced /ʒ/

and /v, z/ for the fricatives. It is noteworthy that the values of ampDiff are significantly lower for voiceless fricatives overall in both groups ($\chi^2(1) = 73.7$; $p < .001$), except for the /f-v/ pair in the CI group.

3.3. Correlation between phonological and acoustical data

The mean values per subject and per phoneme for each type of acoustic measure were compared to assess differences in articulation places (/f/-/s/, /s/-/ʃ/, /v/-/z/, /z/-/ ʒ/) and between voiceless (/f, /s, /ʃ/) and voiced (/v, /z, /ʒ/) fricatives. Correlations between these values and percentages of correct phonemes and fricatives, as well as various types of errors, were examined.

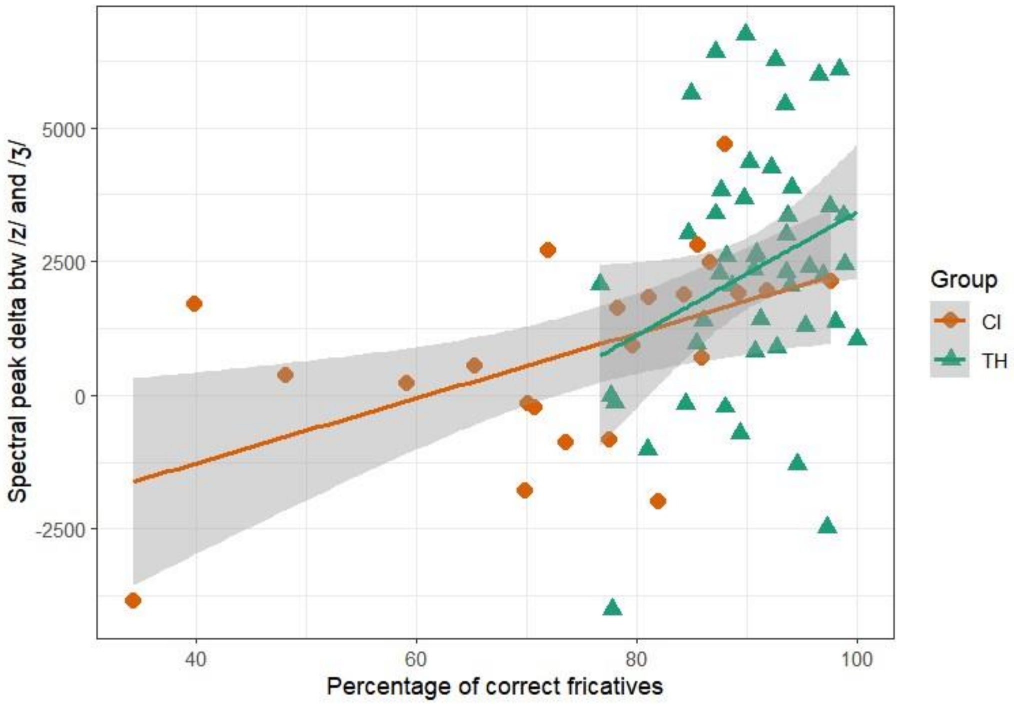

Figure 4.2: Correlations among TH and CI group between PCF and /z/-/ʒ/. spectral peak mean value differences.

A positive correlation was observed in both groups between the percentage of correct fricatives and the average spectral peak values difference between the phonemes /z/ and /ʒ/ (r=0.52; p =.01; see figure 4.2). Additionally, positive correlations were found for the phonemes /s/-/ʃ/ for the CI group (r=0.44; p=0.03) and the TH group for /v/-/ʒ/ (r=0.29; p=0.04). Mean differences in AmpdDiff between voiceless and voiced fricatives were also positively correlated with PCF in the CI group (r=0.42; p=0.05). In the CI group, the fricativization count is negatively correlated with spectral peak mean differences for /v-ʒ/ (r=-0.38; p=0.07), and stopping count is negatively correlated with spectral peak mean differences between /s/ and /ʃ/ (r=-0.45; p=0.03) and /z-ʒ/ (r=-0.53; p=0.009).

4. Discussion

This research aimed to compare potential links between phonological performances and acoustic profiles of fricative consonant in children with CIs and their typically hearing peers. The first part of the analyses involved comparing the accuracy percentages of productions as judged by two listeners, as well as error patterns. Lower accuracy percentages, encompassing all phonemes, and lower percentages of correct fricatives were observed in the CI group. Examining the types of errors revealed specific error patterns in both groups, such as well-documented /s/-/ʃ/ substitutions and devoicings, considered classical errors in language development. Additionally, errors specific to the CI group were identified, including articulatory mode errors (fricativization, stopping) and voicing errors involving voiceless segments. While an effect of chronological age is observed on the percentage of total phonemes and correct fricatives in the TH group, along with a decrease in the number of devoicings and /s/-/ʃ/ substitutions, a chronological age effect is only found in the decrease of /s/-/ʃ/ substitutions in the CI group. The accuracy percentages and the number of other error types are not influenced by chronological or auditory age in the CI group. Although certain error patterns (stopping, devoicing) are consistent with Kim & Chin's (Kim & Chin, 2008) hypothesis of a similar but chronologically delayed development compared to typically hearing peers, the prevalence of certain atypical errors (fricativizations, voicing), and the fact that these different error types do not decrease with chronological/auditory age, seems more in line with the auditory-based hypothesis.

Acoustic analyses revealed overall lower spectral peak values in the CI group and especially for the phonemes /f/, /s/, and /z/. These lower values indicate more energy in the lower frequencies which can be associated with a longer anterior oral cavity, which may be related to a posteriorization of the constriction location and/or a more pronounced lip rounding. Sfakianaki et al. (2024) obtained similar results for the phoneme /s/ in adults with hearing impairments (HI). The authors linked their results to Nicolaidis's study (Nicolaidis, 2004), in which a more pronounced posteriorization of the /s/ phoneme had been highlighted through electropalatography in adults with HI. However, it is noteworthy that the reduction of these values, although diminishing the distinction between the three places of articulation (/f-v/,/s-z/,/ʃ-ʒ/) compared to the TH group, does not result in a lesser distinction of these places of articulation according to our statistical analyses. The observed age effects indeed demonstrate that chronological age advancement in the TH group and auditory age in the CI group are associated with a greater distinction of the voiceless /f-s-ʃ/. Conversely, the voiced /v-z/ in the TH group and /z-ʒ/ in the CI group didn't differ in the older age groups.

Children in the CI group also exhibit overall higher values of levelD and lower values for the AmpDiff measure. These two trends are consistent: children seem to show less reinforcement of amplitudes in mid-frequencies, leading to a decrease in AmpDiff values (differences between low and mid-frequencies), as well as less reinforcement in high frequencies, resulting in a higher levelD (ratio of mid to high frequencies). The reinforcement of mid and high-frequency spectral regions is associated with the strength of the noise source (Shadle et al., 2023); therefore, less reinforcement may be associated with a weaker constriction, resulting in less cancellation of the back-cavity resonances (Koenig et al., 2013). Also noteworthy is that these measurements can distinguish between voiced and voiceless phonemes, with the former marked by a weakening of acoustic energy. While the distinction between voiced and voiceless fricative phonemes is well pronounced in the TH group, evident in both levelD and AmpDiff values, the voicing effect is only found in the distinction between the pairs /s,z/ and /ʃ, ʒ/ within the AmpDiff values in the CI group.

All the acoustic characteristics observed in the CI group within our results appear entirely consistent with the limitations discussed in signal processing by the implant. Indeed, if the implant cannot accurately encode the entire high-frequency range, it may not be capable of transmitting relevant information to 1) distinguish between voiced and voiceless fricative segments and the appropriate degree of constriction; 2) capture higher frequency spectral peaks such as /f, v, s, z/, consequently impacting productive skills. These perceptual limitations, in addition to resulting in distinctive production characteristics, will have a direct impact on phonological development – a conclusion supported by the correlations we have identified. Notably, it has been observed that children in the CI group with better distinction of the /s-ʃ/ and /z-ʒ/ segments by spectral peak values, as well as voiced/voiceless segments by AmpDiff values, also had the highest percentage of correct fricatives and fewer errors in fricativization/occlusivication. This relationship appears consistent with the auditory-based hypothesis of the phonological difficulties of CI users. Moreover, it also highlights that the characteristic variability in the performance of children with CI could be associated with variability in the quality of the auditory signal coded by the implant (for a review, see Başkent et al., 2016) and this interaction with the child's cognitive system's processing of the signal.

5. Conclusion

The study highlighted, on one hand, atypical performance profiles in phonology and phonetics in the production of fricative segments in children with CIs compared to their typically hearing peers. On the other hand, it revealed connections between acoustic and phonetic profiles, where children with more pronounced acoustic distinctions among segments also exhibited better phonological performance. These findings support the hypothesis that the degraded signal transmitted by the implant may be the cause of more pronounced difficulties with certain speech sounds for these children and the variability in their performances.

Chapter 5 Consonant and vowel production: an integrative study

After examining the perception and production skills of nasal vowels in a first group of children with CI and the production of fricative consonants in a second larger group, the present chapter aims to jointly study the production skills of nasal/oral vowels as well as fricative and plosive consonants in the same children, i.e. those forming the latter group. The joint analysis of these three types of segments, which are highly contrasted in terms of acoustic correlates, allows us to better understand the perceptual-productive mechanisms in these children and determine whether distinct profiles of common difficulties and/or compensatory strategies may be observed among the children.

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EDITED BY
Hung Thai-Van,
Institut Pasteur, France

REVIEWED BY
Marie Thérèse Le Normand,
Institut National de la Santé et de la Recherche Médicale (INSERM), France
David Tomé,
Polytechnic of Porto (P.Porto), Portugal

*CORRESPONDENCE
Sophie Fagniart
✉ sophie.fagniart@umons.ac.be

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Consonant and vowel production in children with cochlear implants: acoustic measures and multiple factor analysis

Sophie Fagniart[1,2]*, Brigitte Charlier[3,4], Véronique Delvaux[1,2,5], Anne Huberlant[4], Bernard Georges Harmegnies[1,2,3], Myriam Piccaluga[1,2] and Kathy Huet[1,2]

[1]Language Sciences and Metrology Unit, University of Mons (UMONS), Mons, Belgium, [2]Research Institute for Language Science and Technology, University of Mons (UMONS), Mons, Belgium, [3]Université Libre de Brussels, Free University of Brussels, Brussels, Belgium, [4]Functional Rehabilitation Center "Comprendre et Parler", Brussels, Belgium, [5]National Fund for Scientific Research, Brussels, Belgium

Introduction: The acoustic limitations of cochlear implants (CIs) can lead to perceptual limitations and consequently to imprecise phonological representations and production difficulties. The aim of the study is to document the phonological and phonetic skills of children with CIs and their typically hearing peers. Phonetically, three types of segments were targeted, each characterized by contrasting acoustic information: nasal/oral vowels, fricative segments, and voiced/voiceless stops.

Methods: Forty-seven typically hearing children (TH) and 23 children with CIs performed a picture-naming task. Productions were analyzed to obtain phonological measures (percentages of correct phonemes, types of errors), and various acoustic measures were collected to characterize the productions on the three types of segments investigated. Multiple factor analyses were conducted to study productive profiles on the various acoustic measures, and the dimensions were correlated with phonological measures.

Results: The results showed lower performance in lexical (target word retrieval) and phonological (percentages of correct phonemes) skills among children with CIs (CI group), although with better performances among children exposed to CS. Acoustically, children in the CI group exhibited productions significantly different from those of the TH group in terms of the distinction of fricative consonants, marking nasalization through nasal resonance cues, and in the production of voiceless stops. However, the CI group demonstrated compensatory strategies (lengthening of VOT for voiced stops, marking of nasalization through oropharyngeal configuration cues).

Conclusions: The results indicate that children with CIs are at risk of experiencing difficulties in both phonetic and phonological domains. However, there are opportunities for compensation through the exploitation of acoustic cues better coded by the CI and/or through perceptual means (utilization of visual cues).

KEYWORDS
cochlear implant, speech, acoustic, nasal vowels, fricative consonants, stop consonants, multiple factor analysis

1. Introduction

Cochlear implantation is now commonly provided to people with severe to profound deafness and has been shown to effectively restore hearing function and promote oral language development in children (Sharma et al., 2020; Tamati et al., 2022). However, numerous studies on speech sound production by children with cochlear implants have shown specificities compared to age-matched peers with typical hearing, as well as significant variability in performance. Difficulties in production can be explained primarily by delayed access to oral language associated with a lack of oral language stimulation during sensitive periods in the development of the auditory areas associated with language. Another explanatory factor is related to perceptual difficulties that may arise from processing speech through a cochlear implant, as productive skills require precise support from acoustically and phonologically specified representations (Stackhouse & Wells, 1993). The cochlear implant degrades the spectral structure of sound before transmitting it to the auditory nerve. This degradation is related to the limited number of electrodes capable of independently coding the frequency information of the original sound without activation diffusion or interactions between adjacent electrodes (channel-to-channel interactions). Furthermore, frequency ranges perceived via the implant may be limited in both high and low frequencies. The coding of low frequencies depends on the shallowness of the array insertion and potential mismatches in frequency mapping (Başkent et al., 2016; Başkent & Shannon, 2005). Frequencies above approximately 8000 Hz reach the limits of the processor in current implants (Loizou, 2006; Reidy et al., 2017), meaning that speech sounds with acoustic cues relying on high frequencies are more likely to be perceived and encoded imprecisely by individuals with cochlear implants. The present study aims to investigate how French-speaking children with cochlear implants produce three types of speech segments: nasal and oral vowels, where the distinction is primarily carried by low-frequency information; fricative consonants, where acoustic cues are mainly carried by high-frequency information; and voiced/unvoiced plosive consonants, where the voicing contrast is supported by temporal acoustic cues, presumed to be better encoded by the cochlear implant than spectral cues.

In French, the production of contrastive nasal vowels involves nasal resonance and a specific vowel quality associated with a characteristic oropharyngeal configuration (lip, tongue, and larynx positioning). The acoustic coupling of nasopharyngeal and oropharyngeal cavities results in various acoustic changes compared to oral vowels, including shifts in frequency, intensity, and bandwidth of the first formant (Delattre, 1954; Delattre & Monnot, 1968; House & Stevens, 1956; Maeda, 1993), as well as changes in intensity ratios between the first harmonics and among different formants (Chen, 1995, 1997; Delvaux, 2002; Delvaux & Metens, 2002). These acoustic differences between vowels contrasting for nasalization necessitate the precise processing of acoustic information with a sufficient degree of frequency selectivity and sensitivity to amplitude variations, particularly among low-frequency harmonics, which may pose challenges for cochlear implant recipients. The study of nasal and oral vowels in CI users has been the subject of a limited number of studies, possibly due to the non-contrastive nature of vowel nasalization in many languages worldwide. However, Bouton (Bouton et al., 2012) highlighted difficulties in discriminating minimal pairs based on nasal and oral vowels among French-speaking children with cochlear implants, attributing the challenges to insufficient spectral resolution and difficulty in coding low-frequency information. Borel (Borel, 2015; Borel et al., 2019) noticed challenges in identifying nasal vowels among adult French speakers with cochlear implants, particularly when these vowels were phonetically similar in oropharyngeal configuration to other oral vowels in the French system. This observation led to the development of a discrimination task involving phonologically contrasting nasal and oral vowels (according to the nasal-oral distinction in the French phonological system: /ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/) as well as phonetically divergent pairs in which the oral and nasal vowels were close in terms of oropharyngeal configuration (/ɑ̃/-/ɔ/, /ɔ̃/-/o/, /ɛ̃/-/a/). A recent study (Fagniart et al., 2024a) confirmed these findings in children CI recipients, who have greater difficulty discriminating phonetically matched nasal-oral pairs. Intensive exposure to Cued Speech led to a better utilization of temporal acoustic cues, resulting in improved performance in these children. Subsequent analyses of nasal and oral vowel productions from the same children revealed reduced differentiation based on acoustic cues related to nasal resonance, but increased differentiation based on formant frequencies (i.e. oropharyngeal configuration) and segmental length (Fagniart et al., in press). These results support the hypothesis of increased difficulty in detecting nasal antiresonances and other acoustic cues related with phonetic nasality, although this can be compensated for by exploiting more accessible cues conveying the oral-nasal contrast such as formant values or temporal differences.

The production of fricative consonants involves a constriction in the vocal tract generating turbulent airflow. The resulting aperiodic signal (noise source) covers a wide frequency range with significant energy in the high frequencies. It is then filtered by the vocal tract, resulting in a concentration of energy in the mid to high frequencies depending on the location of the constriction (place of articulation). Due to limitations in processing high frequencies by the implant processor, these segments are prone to causing perceptual and productive difficulties in CI recipients. Identifying and discriminating the places of articulation is more challenging for children with CIs (Bouton et al., 2012; Lane et al., 2001; Mildner & Liker, 2008), especially for the phonemes /s/ and /ʃ/ (Giezen et al., 2010; Hedrick et al., 2011). On the production side, late and imprecise emergence of fricative consonants has been observed in the phonemic repertoires of children with implants, although performance improves with age and duration of CI use (Warner-Czyz & Davis, 2008). Concerning phonological accuracy, some authors (Kim & Chin, 2008) identified typical error patterns in CI children, which are associated with fortition errors (e.g., cessation of fricatives, devoicing). These errors match those observed in the early stages of phonological development in typically hearing children (Jakobson, 1968), suggesting delayed acquisition patterns that are not unique to CI children. In the same vein, Faes & Gillis (2016) have shown that phonological accuracy in fricative consonants is delayed when comparing CI and typically hearing children based on age, but not when matched in terms of vocabulary size. Several acoustic studies have also documented difficulties related to the production of fricatives segments in children with CI compared to their age-matched typically hearing peers, such as : diminished differentiation in the /s/-/ʃ/ contrast (Mildner & Liker, 2008; Reidy et al., 2017; Todd et al., 2011), specific patterns in implementing the /f/-/s/ contrasts in French (Grandon & Vilain, 2020), and overall lower spectral values (Yang & Xu, 2021).

The production of stop consonants involves the active and complete closure of the vocal tract by movements of the articulators towards each other, followed by a quick opening that releases a burst of acoustic energy. In voiced stops, vocal cord vibration accompanies the closing phase, contributing to the addition of a periodic sound source voiced. Voice Onset Time (VOT) serves as the acoustic marker for the voicing contrast in stop consonants. VOT represents the duration of the period of time between the release of the oral closure and the onset of vocal cord vibration (Lisker & Abramson, 1964). Since the voicing contrast in stop consonants is carried by temporal cues, one could presume that it is appropriately encoded by CI. This was suggested by Bouton (Bouton et al., 2012), who noted better performance in children with CIs in discriminating minimal pairs opposing stop consonants on the basis of the voicing feature, compared to other distinctive features. However, this finding has not been consistently verified. For instance, Peng et al. (2019) reported lower performance in discriminating minimal pairs involving voiced vs. voiceless stops among young cochlear implant recipients compared to their hearing peers. Studies using categorical perception paradigms have also yielded contradictory results regarding the performance of children with CIs, with some studies showing lower categorical perception (Giezen et al., 2010), while others did not find any difference when compared to typically hearing children (Medina et al., 2004) for the voicing contrast. Few studies have examined VOT measurements to objectively assess how voiced and voiceless stops are distinguished in the speech productions of children with CI. Uchanski & Geers (2003) and Horga & Liker (2006) observed shorter VOT values for voiceless stops, leading to a reduced voiced-voiceless distinction compared to typical-hearing peers. Grandon et al. (2017) observed shorter VOT values for voiceless stops in French-speaking CI children, but only for the velar consonant /k/. Despite the voicing feature of stop consonants being indicated by temporal cues, studies on the perception and production of this distinctive feature show contrasting results, warranting including them in our study of the speech productions of French-speaking children with CI.

As most studies have focused on a single distinguishing feature in isolation, the main purpose of the present study is to document the productive skills of different types of distinction with the same children, to jointly observe their productive profiles based on phonological and phonetic analysis. To this purpose, we focused on three types of segments: nasal/oral vowels, fricative consonants, and stop consonants, to examine whether there are common production profiles across different types of targeted phonetic features. Productions will be collected through a picture-naming task, to study the phonological representations stored in the children's memory. Taking the literature into account, it can be expected that, children with a cochlear implant (CI):

a) may have difficulty finding the precise phonological form of target words considering their perceptual limitations. These difficulties may manifest in lower naming performance (less retrieval of the target word in the first instance) and/or in more phonemic substitution when producing the target word;
b) may distinguish nasal and oral vowels relying more on better-encoded cues, like formant frequencies related to oropharyngeal configuration rather than nasal resonance cues (Fagniart et al., in press);

c) may produce fricative consonants with less distinction of place of articulation (Mildner and Liker, 2008; Todd et al., 2011; Reidy et al., 2017; Grandon and Vilain, 2020);
d) may produce voiceless stops with shorter values (Uchanski and Geers, 2003; Horga and Liker, 2006; Grandon et al., 2017)

The originality of the study lies in jointly examining these different segments, aiming to identify distinct profiles of common difficulties and/or compensatory strategies that may be observed among the children. In addition to studying these different hypotheses through comparisons between CI children and typical hearing peers, different variables likely to have an impact on performance will also be studied, namely chronological age as well as hearing age, age of implantation and exposure to Cued Speech among CI children.

2. Materials and method

2.1 Participants

Two groups of children were recruited: a group of children with typical hearing (TH group) and a group of children with cochlear implants (CI group). The TH group comprises 47 French-speaking children with typical hearing, with an average age of 56±13 months, who do not exhibit any learning delays or auditory disorders. The CI group consisted of 23 French-speaking children (mean age: 67±15m.) with congenital bilateral profound hearing loss, 22 of whom had bilateral implants, and one child with a unilateral implant. All CI participants received oralist auditory rehabilitation, both at their rehabilitation center and in their family environment. This group was divided based on their exposure to Cued Speech: 8 of the children were not exposed to CS (CS0), while 15 were exposed to CS during their speech therapy sessions (2 at 3 sessions per week) and/or in their family context (CS1). Implantation age groups were also created, with children who received their first implant before 16 months considered as early implantations (CI/EI, n=12), and those implanted after 16 months considered as late implantations (CI/LI, n = 11). The age of 16 months was chosen to be in line with various studies showing a significant benefit from implantation before 18 months (Sharma et al., 2020). Given the distribution of implantation ages, we lowered the threshold to 16 months, enabling us to create equivalent groups. The list of participants and their characteristics are presented in Table 5.1.

Subject	Sex	Chronological age (years ; months)	Chronological age group	Age at first implantation (months)	Implantation age group: early (E) – late (L)	Auditory age group	Implantation type	CS exposure group
CI1	M	4;6	3;7-4;6 y.	9	E	2;6-3;6 y.	Bilateral	CS0
CI2	M	6;5	5;7-7 y.	39	L	2;6-3;6 y.	Bilateral	CS0
CI3	F	5;10	4;7-5;6 y.	15	E	3;7-4;6 y.	Bilateral	CS0
CI4	F	6;7	5;7-7 y.	7	E	3;7-4;6 y.	Bilateral	CS0
CI5	F	6;6	4;7-5;6 y.	31	L	3;7-4;6 y.	Bilateral	CS1
CI6	F	4;7	4;7-5;6 y.	7	E	3;7-4;6 y.	Unilateral	CS1
CI7	F	7;3	5;7-7 y.	13	E	4;7-5;6 y.	Bilateral	CS1
CI8	M	4;7	4;7-5;6 y.	13	E	2;6-3;6 y.	Bilateral	CS1
CI9	M	4;9	4;7-5;6 y.	13	E	2;6-3;6 y.	Bilateral	CS1
CI10	M	4;6	3;7-4;6 y.	12	E	2;6-3;6 y.	Bilateral	CS1
CI11	F	4;6	3;7-4;6 y.	18	L	2;6-3;6 y.	Bilateral	CS1
CI12	M	5;6	4;7-5;6 y.	9	E	2;6-3;6 y.	Bilateral	CS0
CI13	F	7;3	5;7-7 y.	24	L	4;7-5;6 y.	Bilateral	CS1
CI14	G	7;10	5;7-7 y.	26	L	4;7-5;6 y.	Bilateral	CS1
C15	G	6;11	5;7-7 y.	23	L	4;7-5;6 y.	Bilateral	CS1
C16	F	6;9	5;7-7 y.	20	L	4;7-5;6 y.	Bilateral	CS1
C17	M	6;0	5;7-7 y.	20	L	3;7-4;6 y.	Bilateral	CS0
CI18	F	3;9	3;7-4;6 y.	23	L	3;7-4;6 y.	Bilateral	CS0
CI19	F	5;0	4;7-5;6 y.	12	E	2;6-3;6 y.	Bilateral	CS1
CI20	F	3;8	3;7-4;6 y.	32	L	2;6-3;6 y.	Bilateral	CS1
CI21	M	4;11	4;7-5;6 y.	11	E	2;6-3;6 y.	Bilateral	CS0
CI22	F	6;7	5;7-7 y.	17	L	2;6-3;6 y.	Bilateral	CS1
CI23	F	5;0	4;7-5;6 y.	13	E	3;7-4;6 y.	Bilateral	CS1

Table 5.1: Characteristics of the CI children.

Both groups were divided into three/four chronological age groups: 2;6-3;6 years (only for TH group), 3;7-4;6 years, 4;7-5;6 years, and 5;6-7 years (see table 5.2). For children in the CI group, auditory age groups were also formed, considering their age from the time of their first implantation.

Group	Chronological age subgroups years ; months (N)	Auditory age subgroups years ; months (N)
CI	3;7-4;6 y. (5) 4;7-5;6 y. (9) 5;7-7 y. (9)	2;6-3;6 y. (11) 3;7-4;6 y. (7) 4;7-5;6 y. (5)
TH	2;6-3;6 y. (9) 3;7-4;6 y. (10) 4;7-5;6 y. (17) 5;7-7y. (11)	N/A (typical hearing)

Table 5.2: Groups and age subgroups distribution.

2.2 Data collection and treatment

2.2.1 Procedure

Children's speech samples were collected using a picture naming activity (Philippart De Foy et al., 2018). Target words were carefully chosen by the authors to include all French phonemes in initial, medial, or final syllabic position. In addition, these words were selected for their high lexical frequency and early age of acquisition, to facilitate their retrieval by young children. In terms of target segments, the target words contained 25 fricative consonants, 13 nasal vowels and 69 oral vowels, as well as 42 stop consonants.

The target word pictures were presented to the child one at a time via a booklet, and he or she was asked to orally name each picture. Different prompts were provided if the child did not respond or if the produced word did not match the target (semantic paraphasia or random response). First, semantic cues related to the target word were provided (e.g. for example: "you can use it when it rains" for "umbrella".). If the target word was still not produced, a phonological cue was offered by presenting its initial phoneme (e.g. "it starts with /s/" for "/suri/" - mouse). If these two cues were not sufficient for the child to retrieve the target word, the experimenter would produce the target word and ask the child to repeat it. Thus, each target word could be elicited through four types of elicitation: spontaneous naming, naming after semantic prompt, naming after semantic and phonological prompts, or simple repetition. Production based on naming and on repetition can imply different mechanisms: while naming requires retrieval of a phonological form stored in memory, repetition relies on auditory skills while allowing direct imitation of the stimulus. Based on this principle, the effect of the type of elicitation (direct naming or prompt vs. repetition) will also be studied within productions. The children's productions were recorded using a H5 Zoom portable recorder.

2.2.2 Phonological analysis

All the audio files were annotated by an initial examiner and subsequently verified by the first author using the Phon 3.1 software (Hedlung & Rose, 2020). By comparing them with the canonical phonological content of the target words, these annotations made it possible to the extraction of the Percentage of Correct Phonemes (PCP), Correct Fricatives (PCF), Correct Nasal vowels (PCN), Correct Stops (PCS) and to identify the various types of production errors made by the children such as substitution based on place or manner of articulation or voicing.

2.2.3 Acoustic analysis

The annotations performed in Phon were subsequently exported to Praat (Boersma & Weenink, 2023). Phoneme alignments were manually corrected to enable the use of semi-automated scripts for extracting acoustic measures on the segments of interest.

2.2.3.1 Nasal vowels

The acoustic description of vowels aimed to study the two main aspects of nasal/oral vowel production: the adoption of an articulatory configuration specific to the vowel quality, on one hand, and the resonance with the nasal cavities (only for nasal vowels) on the other hand. To investigate the acoustic characteristics associated with oropharyngeal configuration, formant values were examined. For the study of nasal resonance, Nasalization from Acoustic Features (NAF) values (Carignan et al., 2023) were generated. A total of 6605 vowels were analyzed.

Formant measurements were obtained using a semi-automated procedure. For F1, F2 and F3, the formant value used is the median value of the series of values obtained every 5ms in the interval between 25% and 75% of the total vowel duration. Given the sensitivity of formant value detection to spectrogram parameters, particularly in children, several precautions and verifications were implemented to avoid errors in formant detection. Initially, formant detection parameters were adjusted individually for each vowel and child. After extracting the formant values based on these parameters, a visualization of the productions in the F1/F2 space was utilized to identify any aberrant values. Aberrant values were identified by checking if F1, F2, or F3 values fell beyond plus or minus three standard deviations from the mean formant values of the subject. All outliers were manually verified, with spectrograms examined to correct formant values or exclude vowels with unreadable or unclear signals (with a negligible number of occurrences, around 1%).

To assess the degree of nasality in the vowel productions, a procedure largely inspired by the NAF (Nasalization from Acoustic Features) method (Carignan, 2021; Carignan et al., 2023) was employed. First, a large array of measures was collected through semi-automated procedures to extract acoustic indices at eleven time points within the vowels. These measures included overall amplitude, formant bandwidths for F1, F2 and F3, as well as relative amplitude deltas between formants and poles : A1-P0, A1-P1, A3-P0 (measured using the "Nasality Automeasure Praat" script by Styler, 2017) and various indices proposed by Carignan (spectral moments and nasal murmur). Note that some acoustic indices used in Carignan's initial method, such as formant frequency values and Mel-frequency cepstral coefficients (MFCC), were not included here since effects pertaining to oropharyngeal configuration alterations were measured separately with formant values. Secondly, a model was built to reduce the various acoustic cues linked to vowel nasality to a value that would characterize the oral-nasal dimension. Indeed, it is currently complicated to isolate a single acoustic metric to reflect the degree of nasal resonance (Carignan, 2021). Based on this principle, we drew inspiration from the NAF method to build a machine learning model that predicts a metric value quantifying the oral/nasal character of children's productions based on the series of acoustic cues collected. A supervised machine learning technique was employed: the gradient-boosted decision tree model. This technique necessitates training the model on a portion of the data, requiring a training and test sample. For this purpose, part of the time points over which acoustic measurements were collected within each vowel were used for training, the other for testing. To avoid capturing the effects of pre- and post-vocalic phonetic context, we excluded the time points corresponding to the 0, 10, 90, and 100% portions of the vowel, leaving 7 time points. Next, we partitioned the dataset by extracting the time points at 20, 40, 60, and 80% of the duration of each vowel from the children in the TH group to form the training sample. We chose to include these time points because they represent a relatively stable portion of the vowel that is most likely to carry information related to vowel nasality. The training sample was made up of children from the TH group only, so that the model could be trained on supposedly typical productions. Within the training sample, productions were labeled as oral (0) or nasal (1) based on the target vowel to be produced. Subsequently, a gradient-boosting decision tree model (XGBoost R Package, Chen and Guestrin, 2016) was trained on the scaled selected acoustic features with multiple iterations to optimize hyperparameters and minimize cross-validation errors. Finally, the trained model was used to predict nasality responses on the testing sample. The model was defined with minimized linear regression error, to permit the obtention of values on a scale from 0 to 1 on an oral-nasal mapping dimension. The resulting NAF values ranged numerically from 0 to 1, with higher values indicating a higher predicted degree of nasality, and intermediate values corresponding to those that are halfway to the acoustic characteristics of nasal and oral vowels.

To examine strategies employed in the phonetic implementation of the phonological contrast between nasal and oral vowels, paired comparison analyses were conducted, considering the phonetic (/ɑ̃/-/ɔ/, /ɔ̃/-/o/, /ɛ̃/-/a/) and phonological (/ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/) proximity (Borel, 2015) of oral-nasal pairs in French. We also included the pairs /ɑ̃/-/o/, as the distinction between /o/ and /ɔ/ is sometimes subtle in children's productions, and /ɔ̃/-/u/, as these segments are also very close phonetically (Fagniart et al., 2024a). For each child, each produced nasal vowel was paired with all orally produced vowels that were phonetically or phonologically similar, resulting in a listing of all oral/nasal pairs produced. A total of 30,402 pairs were formed, allowing for comparisons of acoustic cues within each nasal-oral pair. Euclidean distances in the F1-F2-F3 (Bark) planes (as described in Calabrino, 2006) and differences between NAF values were examined for each pair.

2.2.3.2 Fricative consonants

The acoustic characterization of fricative consonants was conducted using recently developed measures (Shadle et al., 2023), allowing for the examination of both the place of articulation, i.e., the location of airflow obstruction, and the quality of the frication noise generated by analyzing intensity ratios across low, mid, and high-frequency bands. These measurements were conducted within spectra generated by the Multitaper Method (MTPS) (Blacklock, 2004), which averages a series of periodograms obtained through the collection of mutually orthogonal windows (tapers). The MTPS method is renowned for its minimized errors and enhanced temporal precision (Sfakianaki et al., 2024).

A total of 1917 fricatives were analyzed. A R script adapted from the script developed and provided by P. Reidy (2018) generated a MTPS using 8 tapers at the temporal midpoint of the phoneme. Three acoustic measures were then collected from the generated spectra: spectral peak, levelD, and ampDiff for each target sibilant /s,z,ʃ,ʒ/ or ampRange for each target non-sibilant /f-v/. The spectral peak was obtained by extracting the frequency of the amplitude peak in the mid frequencies, levelD was obtained by calculating the difference in acoustic power between mid and high frequencies, and ampDiff represented the amplitude difference between low and mid frequencies. It is worth noting that the indices levelD and ampDiff quantify the energy ratios in low, mid, and high frequencies. A good frication noise source should have a significant portion of acoustic energy in mid and, particularly, high frequencies. Therefore, a good noise source should result in high ampDiff values (as mid frequencies are reinforced compared to lows) and low levelD values (indicating a large proportion of energy in high frequencies). These three measures required the definition of ranges for low, mid, and high frequencies within the spectrum. Since there were no references available for young children, these ranges were established through a meticulous analysis of the spectra, employing trial-and-error to identify parameters that most accurately represented our data. Finally, the values proposed by Shadle for adult females (Shadle et al., 2023) with slight modifications were adopted. Notably, the maximum threshold for the mid-frequency range in the detection of spectral peaks for /s, z/ was adjusted to 10000 Hz instead of 8000 Hz, and to 8000 Hz instead of 4000 Hz for /ʃ, ʒ/.

2.2.3.3 Stop consonants

A total of 3012 stops were analyzed. To calculate VOT, stop consonants were manually annotated on Praat by identifying the consonant burst, which represents the moment of stop release, and the onset of voicing, which could precede the burst in the case of voiced consonants or follow it in the case of voiceless consonants. Subsequently, a Praat script was used to extract the VOT of all the annotated stops.

2.3 Statistical analysis

Linear generalized mixed models, employing the lme4 package (version 1.1-34; Bates et al., 2015) within the R software (R Core Team, 2022), were used to compare groups among the various acoustic measures on the children's speech productions. These models were constructed by including subject and stimulus characteristics (the variables and their levels are specified in Table 5.3) and the interaction among these variables. It is worth noting that it was the expected segments relative to the target word that allowed for labeling the identity of the productions. For example, the /ɑ̃/ in "pantalon" (/pɑ̃talɔ̃/ - "pants") was labeled as /ɑ̃/ regardless of the actual production of the segment, i.e. even if it was denasalized. To address inter-subject variability, a random intercept effect for the subject was integrated into the model. Significance assessment of fixed effects were examined using Chi-squared tests and corresponding p-values, conducted via the ANOVA function of the Car package (Fox and Weisberg, 2018) applied to the model. Additionally, post-hoc analysis were conducted using the emmeans package (Lenth et al., 2023).

LGM Variables	Variables and their levels
Subject characteristics	Auditory status: cochlear implant children (CI) – typical hearing children (TH) CS exposure : CI/CS0 = no CS exposure - CI/CS1 = CS exposure - TH Chronological age group: 2;6-3;6 / 3;7-4;6 / 4;7-5;6 / 5;7-7 Auditory age group: 2;6-3;6 / 3;7-4;6 / 4;7-5;6 / 5;7-7 Implantation age group : CI/EI = early (< 16m.) – CI/LI = late (> 16 m.) – TH
Stimulus characteristics	Segment identity: - Nasal/oral pair: /ɑ̃/-/a/, /ɑ̃/-/ɔ/, /ɑ̃/-/o/, /ɔ̃/-/ɔ/, /ɔ̃/-/o/, /ɔ̃/-/u/, /ɛ̃/-/ɛ, /ɛ̃/-/a/ - Fricative consonants: /f/-/s/-/ʃ/-/v/-/z/-/ʒ/ - Stop consonants: /p/-/t/-/k/-/b/-/d/-/g/ Voicing type: voiced - voiceless (for fricative and stop consonants) Elicitation type: naming - repetition

Table 5.3: Variables related to subject and stimulus characteristics and their levels.

Multiple factor analyses were conducted using the FactoMineR package (Husson et al., 2024), and graphical representations were created using Factoextra (Kassambara & Mundt, 2020). They were performed on a dataset consisting of subject-wise averages of various acoustic measures aggregated as means, namely:

- Euclidean distance values of F1-F2-F3 and NAF for all nasal-oral pairs, where higher average values indicate a greater distinction between nasal and oral configurations in terms of oropharyngeal configuration and nasal resonance.
- Spectral peak values by place of articulation, averaged levelD and ampDiff for fricatives, where one would expect to observe better articulation places marked by higher and well-distinguished spectral peak values, lower values for levelD, and higher values for ampDiff, representing a reinforcement of high-frequency acoustic energy associated with a good frication source (Shadle et al., 2023);
- Mean differences between VOT values of voiceless and voiced stops, where higher values indicate a greater distinction in voicing between voiced and voiceless stops.

The subjects' characteristics (hearing status, age groups, CS exposure) were added as supplementary variables not actively involved in constructing the dimensions. This addition allows for observing the distribution of different subgroups based on the constructed dimensions. The description of the generated dimensions along with their constituent variables and the additional variables was performed using the dimdesc function (package FactoMineR). Finally, to determine whether a relationship exists between children's phonological performance and their acoustic profiles, we conducted Pearson correlations between the dimensions of the multiple factorial analysis and the various phonological accuracy scores obtained.

3. Results

3.1 Naming task performance

As explained in section 2.2.1, children produced all target words of the naming task but may have done so using different types of elicitation: spontaneous naming or after semantic prompt, after semantic and phonological prompts, or through simple repetition. The percentages of the first type of elicitation, spontaneous naming, are significantly higher in the TH group (84.4%) than in the CI group (77.4%; $\chi^2(1)= 4.96$; $p=.02$). No group effect is observed for the second type of elicitation, i.e. naming on semantic cue (TH: 2.79%; CI: 1.96%; $\chi^2(1)= 1.26$; $p=.26$), while the third, based on phonological priming, is found significantly more frequently in the TH group (6.22% ; CI: 2.03% ; $\chi^2(1)= 10.05$; $p=.001$). Production based on repetition of the target word, the fourth type of elicitation, is significantly more common among children in the CI group (18.38%; TH: 5.95%; $\chi^2(1)=17.06$; $p<.001$). An effect of CS exposure is observed on the percentage of spontaneous naming (elicitation 1): only children in the CI/CS0 group differ significantly from the TH group (70.8%; t(67)=-13.65; p=.02), with the CI/CS1 group showing similar performance (80.3%; t(67)=-4.15; p=.47). No effect of chronological or auditory age or age of implantation group was observed.

3.2 Phonological analysis

The percentages of correct phonemes are analyzed to document phonological accuracy. Children in the CI group have significantly lower percentages of correct total phonemes (CI: 77.5% - TH: 91.1% ; $\chi^2(1)$= 31.87; p<.001), correct nasal vowels (CI: 74% - TH: 91.5%; $\chi^2(1)$= 35.43; p<.001), correct fricative consonants (CI: 74.3% - TH: 90.4%; $\chi^2(1)$= 36.67; p<.001) and correct stop consonants (CI: 76.9% - TH: 90.7%; $\chi^2(1)$= 29.07; p<.001). Table 5.4 presents the percentages of different error types on the target segments. The most frequently observed error type is denasalization of nasal vowels with significantly higher rate than TH children ($\chi^2(1)$= 27.07; p<.001). Fricativization ($\chi^2(1)$=10.19; p=.001) and stopping ($\chi^2(1)$=10.8;p=.001) errors are also retrieved at a significantly higher rate in the CI group as well as voicing of voiceless stops ($\chi^2(1)$=25.96; p<.001), these errors being negligible in the TH group (<1%). Devoicing errors are retrieved in the two groups, with a marginally higher rate in the CI group ($\chi^2(1)$= 3.04=p=.08) while nasalization of oral vowels is negligible in the two groups.

Measure	Group performances (%)				Significance of group comparison tests			
	CI	CS0	CS1	TH	CI/ TH	CS0/ CS1	CS0/ TH	CS1/ TH
% correct phonemes (PCP)	77.5	72.5	79.6	91.1	***		***	**
% correct nasal vowel (PCN)	74.0	65.7	77.6	91.5	***	*	***	***
% correct fricatives (PCF)	74.3	69.4	76.5	90.4	***		***	***
% correct stops (PCS)	76.9	71.7	79.2	90.7	***		***	***
% vowel nasalization	0.53	1.28	0.2	0.16		**	***	
% vowel denasalization	15.25	23.23	11.76	2.65	***	*	***	**
% voicing errors	2.94	3.33	2.77	0.41	***		**	***
% devoicing errors	5.14	3.33	5.93	3.72				*
% stopping errors	3.37	3.33	3.38	0.56	**			*
% fricativization errors	1.29	2.26	0.87	0.31	**	*	***	

Table 5.4: Percentage correct phonemes among the Cochlear Implant (CI) and Typically Hearing (TH) groups. ns, *p<.05, **p<.01, ***p<.001

CS exposure displays a significant effect on the correct percentages of nasal vowels ($\chi^2(2)$= 43.14; p<.001), with the CI/CS1 group showing significantly higher score than the CI/CS0 group (77.6 vs. 65.7; t(67)=-11.8; p=.05) but lower than the TH group (t(67)=-13.9;p<.001). As for the different error types, the CS/CS0 group also shows higher percentages of nasalization of oral vowels and of fricativization of stops than the two other groups. For nasal vowels denasalization, the CI/CS1 group show lower error percentages than the CI/CS0 group but the percentage remain higher than the TH group. Devoicing of voiced stops was observed at a higher percentage in the CI/CS1 group compared to the two others. No effect of chronological or auditory age was observed, nor were there any effects of the age group at implantation.

3.3 Acoustic analysis

Table 5.5 presents the means, as well as the significance of the associated group comparison tests, for the various acoustic measurements carried out on the studied segments, grouped according to auditory status (TH vs CI) and exposure to CS (CS0 vs CS1).

Segment type	Measure	Target vowel	Group means				Group comparison tests			
			CI	CI/CS0	CI/CS1	TH	CI - TH	CS0 - CS1	CS0 - TH	CS1 - TH
Vowel	E.D. F1-F2-F3 (brk)	/ɑ̃/ - /a/	4.41	4.39	4.42	4.6				
		/ɑ̃/ - /ɔ/	3.62	3.34	3.72	3.49				
		/ɑ̃/ - /o/	3.45	3.97	3.28	3.06	*	*	**	
		/ɔ̃/ - /ɔ/	4.01	3.5	4.19	3.68	*	*		*
		/ɔ̃/ - /o/	3.42	3.47	3.42	2.74	***		*	**
		/ɔ̃/ - /u/	3.32	3.52	3.27	2.84	**		*	*
		/ɛ̃/ - /ɛ/	3.97	3.37	4.17	4.01		*	*	
		/ɛ̃/ – /a/	3.14	3.11	3.16	2.86	.06			
	delta NAF	/ɑ̃/ - /a/	0.114	0.08	0.13	0.17	***		**	*
		/ɑ̃/ - /ɔ/	0.019	0.002	0.027	0.06	***		*	
		/ɑ̃/ - /o/	0.071	0.034	0.087	0.127	**		**	*
		/ɔ̃/ - /ɔ/	0.052	0.05	0.05	0.11	***		**	*
		/ɔ̃/ - /o/	0.109	0.097	0.114	0.178	***			**
		/ɔ̃/ - /u/	0.051	0.062	0.045	0.08	*			*
		/ɛ̃/ - /ɛ/	0.076	0.05	0.08	0.113	*			
		/ɛ̃/ - /a/	0.08	0.06	0.09	0.124	**		*	*
Fricatives	Spectral peak (Hz)	/f/	6689	6009	6990	7611	***	*	***	*
		/s/	6085	5749	6232	6702	**		*	
		/ʃ/	4720	4207	4943	5014		.08	*	
		/v/	6421	5948	6620	6618				
		/z/	5775	5284	5981	6925	***		**	*
		/ʒ/	4921	4302	5198	4587				
	levelD (dB)	/f/	6	7.81	5.21	3.93	*		**	
		/s/	6.98	8.89	6.17	2.72	**		***	**
		/ʃ/	8.27	10.4	7.34	7.29		.07	*	
		/v/	5.19	5.13	5.17	5.26				
		/z/	6.99	7.96	6.57	1.89	***		***	***
		/ʒ/	8.46	10.23	7.67	9.23				
	ampDiff (dB)	/f/	13.99	13.69	14.13	13.13				
		/s/	19.09	22.23	17.77	16.91	*	*	**	
		/ʃ/	19.11	20.43	18.55	19.38				
		/v/	12.93	14.6	12.26	11.42				

		/z/	16.16	13.15	17.34	13.21	**	.08		**
		/ʒ/	16.06	16.54	15.84	16.63				
Stops	**VOT (ms)**	**/p/**	23	29.6	20.1	32.1	*			*
		/t/	34	33	34.4	44.6	*			
		/k/	38.2	34.8	39.7	45.3				
		/b/	-57.3	-67.5	-53.4	-48.9	.07		*	
		/d/	-78.8	-87	-75.7	-57.3	*		.09	
		/g/	-42.6	-60.2	-36.7	-36.6				

Table 5.5: Acoustic analysis according to auditory status and exposure to Cued Speech (CS). Legend: ns, *p<.05, **p<.01, ***p<.001

3.3.1 Nasal/oral vowels

This section will focus on the analysis of acoustic differences within pairs of nasal-oral vowels. Formant and NAF values averaged per target phoneme and per child group, as well as the p-values associated with group difference tests, are available in Table 5.5. Considering nasal-oral pairwise comparisons in terms of Euclidean distances in the F1/F2/F3 plane, an auditory group*pair interaction is observed ($\chi^2(7) = 201.6$; $p < .001$). The CI group exhibits higher values for 5 out of 8 pairs, indicating a greater differentiation in terms of oropharyngeal configuration for these pairs, namely /ɑ̃/-/o/, /ɔ̃/-/o/, /ɔ̃/-/ɔ/, /ɔ̃/-/u/, and /ɛ̃/-/a/ pairs (see Figure 5.1). An interaction between elicitation type (naming vs. repetition), pair, and group is observed ($\chi^2(21) = 330.6$; $p < .001$). Indeed, the CI group show higher Euclidean distances between oral and nasal vowels in the repetition condition for all pairs except /ɑ̃/-/a/ and /ɛ̃/-/a/, while the TH group shows higher values in the repetition condition for /ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/a/, and /ɛ̃/-/ɛ/. A significant CS exposure group*pair interaction is also found ($\chi^2(14) = 309.55$; $p < .001$), with the TH group showing lower values than the CI/CS0 and CI/CS1 groups for /ɔ̃/-/o/ and /ɔ̃/-/u/, while the CI/CS0 group shows the highest values compared to other groups for /ɑ̃/-/o/ and the lowest for /ɛ̃/-/ɛ/. An interaction between elicitation type (naming vs. repetition), pair, and CS exposure group is also observed ($\chi^2(35) = 466.1$; $p < .001$). While the CI/CS1 group showed higher values in the repetition condition for all the pairs except /ɛ̃/-/a/, the CI/CS0 group is characterized by higher values only for /ɔ̃/-/u/ and /ɛ̃/-/a/, with, conversely, lower values in the repetition condition for /ɛ̃/-/ɛ/ and /ɑ̃/-/a/. An interaction between chronological/auditory age group, auditory status group, and pair is observed. Indeed, an auditory age group effect is only observed in the /ɔ̃/-/u/ pair, with decreasing values for age groups following 3;7-4;6. In the TH group, a chronological age group effect was observed in /ɑ̃/-/a/, /ɑ̃/-/ɔ/, and /ɑ̃/-/o/, with decreasing values in older age groups. When comparing the groups based on age of implantation, there's an observed interaction effect between the age of implantation groups and pair ($\chi^2(14) = 299.1$; $p < .001$). Specifically, the group of children with later implantation (CI/LI) shows significantly higher values than the group of children with early implantation (CI/EI) for the pair /ɔ̃/-/ɔ/.

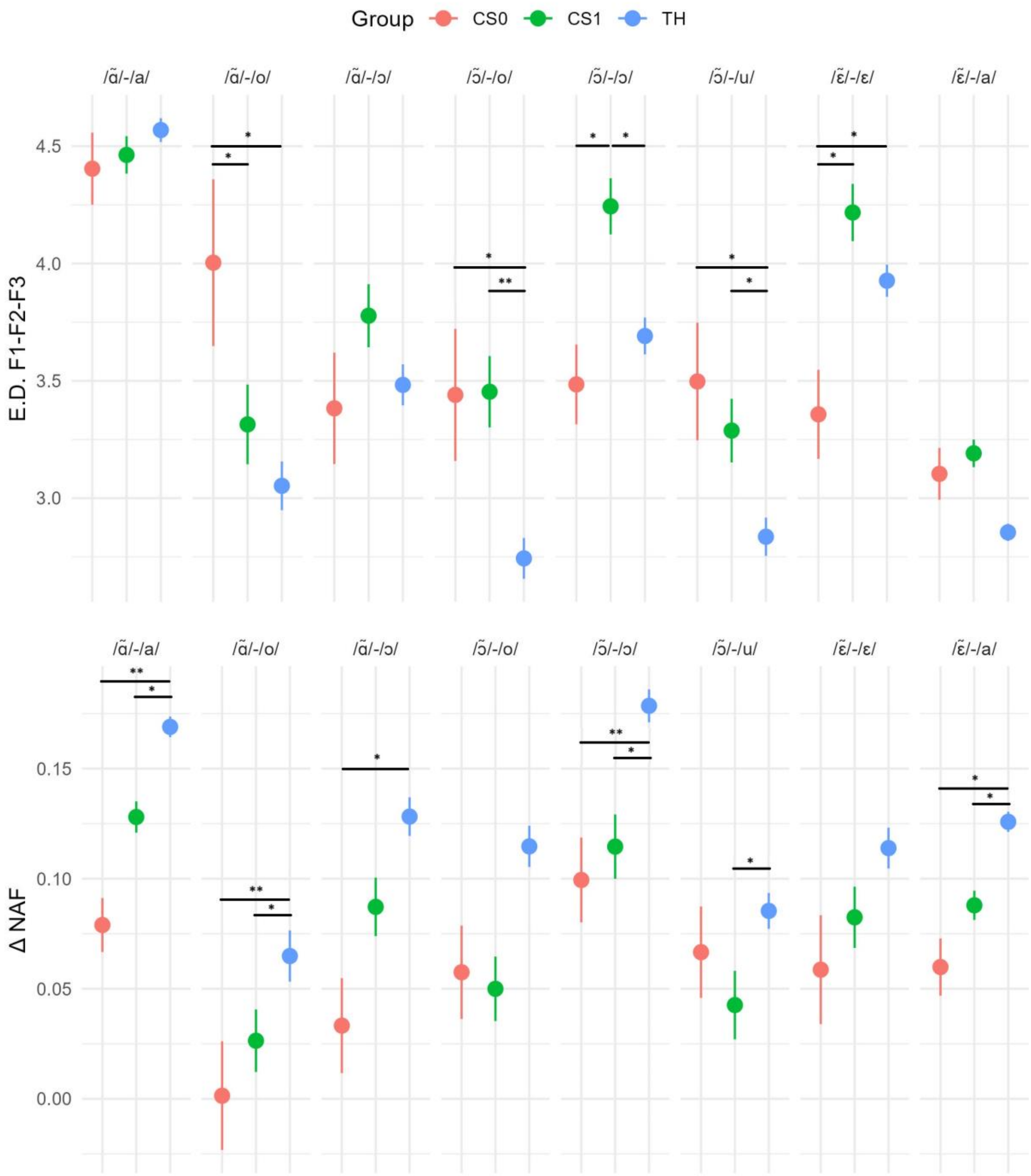

Figure 5.1: Means and 95% confidence intervals of the Euclidean distances and delta NAF values for the different nasal/oral pairs among the CS exposure groups (TH, CI/CS0, and CI/CS1).

The statistical analysis of nasal/oral differences in terms of NAF values revealed an interaction between auditory status group and pair ($\chi^2(7) = 201.5$; p< .001), with significantly higher values in the TH group for the /ɑ̃/-/o/, /ɔ̃/-/o/, /ɔ̃/-/ɔ/, /ɔ̃/-/u/ and /ɛ̃/-/a/ pairs. An interaction between elicitation type, group, and pair ($\chi^2(21) = 155.9$; p < .001) was also observed. Indeed, while TH children benefited from repetition which results in an increase in nasal-oral differences in terms of NAF for the pairs /ɑ̃/-/a/, /ɑ̃/-/ɔ/, /ɔ̃/-/ɔ/ and /ɔ̃/-/u/, for children in the CI group this is only the case for the pairs /ɛ̃/-/ɛ/ and /ɛ̃/-/a/. On the contrary, children in the CI group showed a decrease in NAF values in the repetition condition for the pairs /ɑ̃/-/a/, /ɑ̃/-/ɔ/, /ɔ̃/-/o/, /ɔ̃/-/ɔ/ and /ɔ̃/-/u/. Considering CS exposure, an interaction between CS exposure and pair is observed ($\chi^2(14) = 131.6$; p < .001). Indeed, the CI/CS0 group had lower values compared to the two other groups for the /ɔ̃/-/o/ pair and lower compared to the TH group for the /ɑ̃/-/ɔ/ pair. The TH group shows the highest values compared to the other groups for the /ɛ̃/-/a/ pair. An interaction between elicitation type and CS exposure group ($\chi^2(2) = 62$; p < .001), as well as between elicitation type, CS group, and pair ($\chi^2(35) = 280.9$; p < .001), was observed. Indeed, while children in the TH and CI/CS0 groups benefited from the repetition condition by seeing their nasal/oral difference values in terms of NAF increase, children in the CI/CS1 group see their overall values decrease. The increase in values in the repetition condition was found significant in the TH group for the /ɑ̃/-/a/ pairs, /ɑ̃/-/ɔ/, /ɔ̃/-/ɔ/, /ɔ̃/-/u/ and in the CS0 group for the pairs /ɑ̃/-/ɔ/, /ɔ̃/-/u/, /ɛ̃/-/ɛ/ and /ɛ̃/-/a/. In the CS1 group, values were significantly lower in the repetition condition for the pairs /ɑ̃/-/ɔ/, /ɔ̃/-/ɔ/, /ɔ̃/-/u/. Again, an interaction between chronological/auditory age group, auditory status group, and pair is observed ($\chi^2(52) = 323.2$; p < .001). Indeed, a chronological age effect was observed for /ɑ̃/-o/, /ɔ̃/-o/, /ɛ̃/-ɛ/ and /ɛ̃/-/a/ in the TH group with no increasing chronological/auditory age effect on values in the CI group. In comparing the groups formed on the basis of age of implantation, an interaction effect between age of implantation and the pair is observed ($\chi^2(14) = 108.1$; p < .001). Specifically, the group of children with early implantation (CI/EI) exhibited significantly higher values than the group of children with later implantation (CI/LI) for the pair /ɔ̃/-/ɔ/.

3.3.2 Fricative consonants

Concerning spectral peak values, an auditory status group effect is observed, indicating lower values in the CI group ($\chi^2(1) = 9.4$; $p = 0.002$). A significant interaction effect is observed between group and phoneme type ($\chi^2(5) = 23.9$; $p < 0.001$), with significant group differences noted for the phonemes /f/, /s/, and /z/, suggesting a more posterior place of articulation for these segments in the CI group (see Figure 5.2). This spectral peak decreased values have an impact on the distinction of the different places of articulation : the CI group shows no significant differences between places of articulation among the voiceless /f/-/s/, /s/-/ʃ/ and the voiced fricatives /v/-/z/ and /z/-/ʒ/, while this phonemes are significantly distinguished in the TH group (/f-s/ : $z = 5.8$; $p<.001$ - /v-z/ : $z = 11.2$; $p<.001$ - /z/-/ʒ/ : $z =10.8$; $p<.001$). An elicitation type*auditory status group interaction effect is observed ($\chi^2(5)=506.6$; $p=.05$). Indeed, while the repetition condition led to increasing spectral peak values in the TH group, it led to decreased values in the CI group. This effect is significant in the TH group for /f/ (naming: 7566Hz - repetition: 9342Hz; $t(1890)=-2.5$; $p=.01$) and marginal in the CI group for /v/ (naming : 6538Hz - repetition : 4641Hz ; $t(1890)=1.8$; $p=.07$). An interaction between chronological/auditory age group, auditory status group and phoneme effect is observed ($\chi^2(35) = 66.0$; $p = 0.001$) : while no chronological/auditory group effect appears in the CI group, an effect of chronological age is observed in the TH group, with spectral peak values decreasing with age for /f/ and /s/, resulting in improved distinction of articulation places among voiceless fricatives /f/, /s/, /ʃ/. A CS exposure grouping effect ($\chi^2(2)=14.7$; $p<.001$) as well as an interaction between CS grouping and phoneme ($\chi^2(10)=28.4$; $p=.001$) are obtained : spectral peak values are significantly lower in the CI/CS0 group compared to the TH group ($z= -3.5$; $p=.001$) and marginally to the CI/CS1 groups ($z=-2.1$; $p=.09$), while the TH and the CI/CS1 group had similar mean values. Regarding phoneme type, CI/CS0 had significantly lower values for /f/ compared to TH ($z= -4.4$; $p<.001$) and CI/CS1 group ($z= -2.7$; $p=.02$), as well as marginally lower values than TH group for /ʃ/ ($z= -2.1$; $p=.08$) and /v/ ($z = -2.2$; $p= .08$). For /s/ and /z/, TH group has significantly higher spectral peak values than the other two groups. An effect of age of implantation group ($\chi^2(2) = 10.1$; $p = .006$) as well as an interaction between age of implantation group and phoneme type is observed ($\chi^2(10) = 30.5$; $p < .001$). Specifically, values are generally lower in the late implantation group compared to the TH group ($z = -2.9$; $p = .008$), with this difference being significant for the phoneme /z/ ($z = -3.6$; $p < .001$).

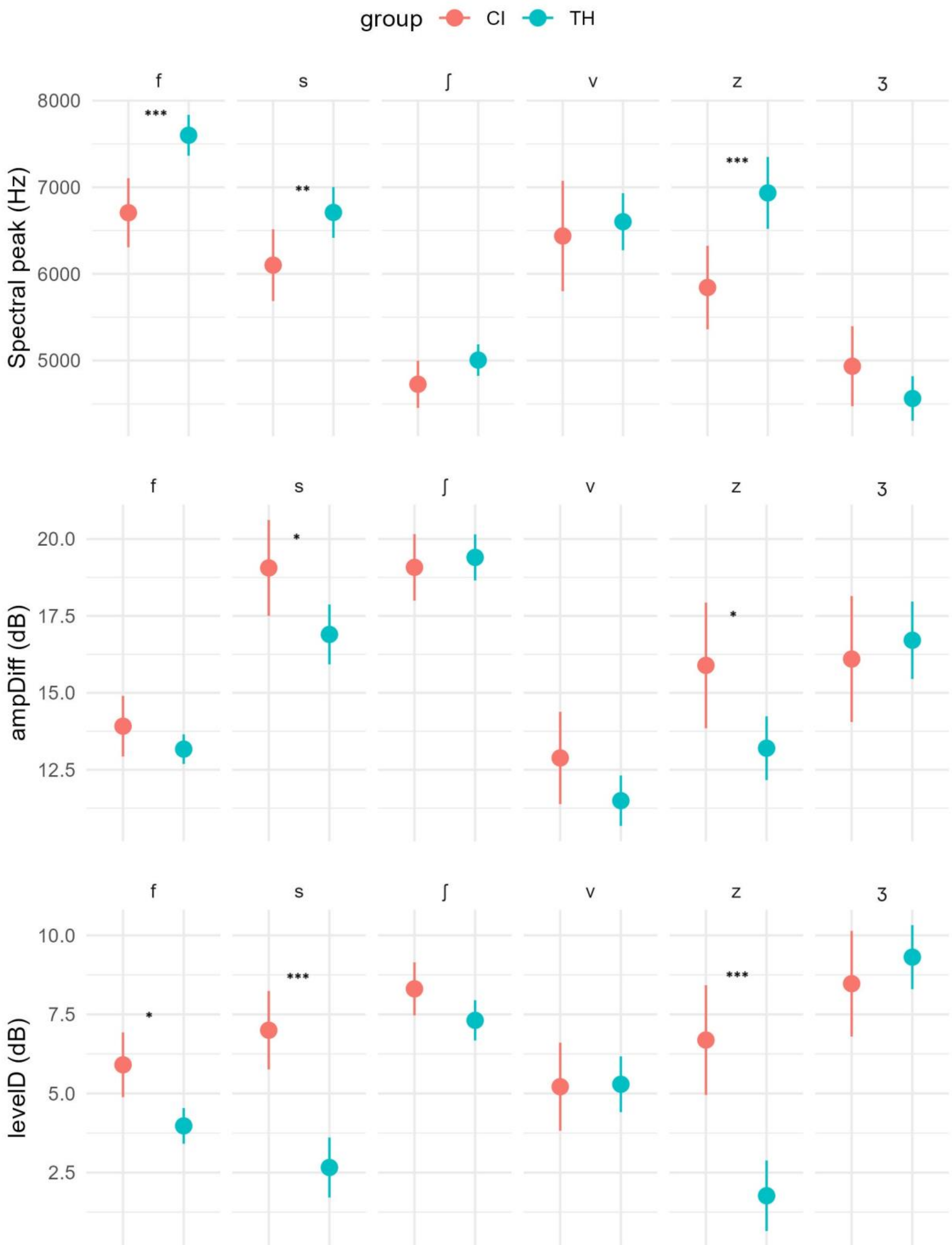

Figure 5.2: Means and 95% confidence intervals of the spectral peak, ampDiff and levelD values of the different fricative segments of the CI and TH groups.

AmpDiff values, which reflects amplitude differences between mid- and low-frequency ranges within the fricative spectrum, exhibited an auditory status group effect ($\chi^2(1) = 3.5$; p =.05), with lower values in the TH group, as well as a group*phoneme interaction effect ($\chi^2(5) = 13.5$; p =.02) with significantly lower values in the TH group for /s/ (z= 2.8 ; p=.004) and /z/ (z= 2.9 ; p=.003). The higher values observed in the CI group may indicate greater reinforcement of mid-frequency areas compared to TH children. No elicitation type effect was observed. A voicing type effect is observed ($\chi^2(1)= 71.6$; p<.001), with a significant decrease of the voiced fricatives ampDiff values in the TH (z = 7.4 ; p<.001) and the CI group (z= 4.3; p<.001), as expected. An interaction between chronological/auditory age group, auditory status group and phoneme are obtained ($\chi^2(15) = 56.7$; p<.001) : ampDiff values increase with chronological age in the TH group for all phonemes except /f/, while CI group displays a decrease of the values in the older auditory age group for /s/. An interaction between CS exposure and phoneme is observed ($\chi^2(10) = 34.4$; p<.001), with significantly higher values in the CI/CS1 group compared to the CI/CS0 (z= -2.3 ; p=.06) and TH groups (z = 3.5 ; p=.001) whereas the CI/CS0 group had significantly higher AmpDiff values for /s/ compared with the TH group (z = 2.9 ; p=.01). No effect of implantation group is observed on the ampDiff values.

Regarding the levelD values, which reflects sound level differences between the mid- and high frequency ranges, a significant group effect was observed, with significantly higher values in the CI group ($\chi^2(1) = 5.6$; p =.01) as well as a group*phoneme interaction effect ($\chi^2(5) = 98.6$; p < 0.001), with values significantly higher for /f/, /s/ and /z/ in the CI group. The higher values of the levelD values in the CI group indicate less reinforcement of high frequencies compared to children in the TH group. An interaction between elicitation type and group was observed ($\chi^2(5) = 47.4$; p<.001), with repetition condition leading to higher levelID values in the CI group only (naming: 6.7dB – repetition: 8.9dB ; t(1891) = -2.4; p=.01). This trend was significant for /v/ in the CI group (naming : 4.8dB – repetition : 10.3dB ; t(1869) = -1.9; p=.04), while in the TH group the repetition condition led to significantly decreased values for /f/ (naming : 3.9dB – repetition : 0.2dB ; t(1832) = 2.1 ; p=.03) and marginally so for /ʃ/ (naming : 7.3dB – repetition : 3.4dB ; t(1835) = 1.9 ; p=.06). Considering voicing, a marginal group*voicing interaction effect was observed ($\chi^2(1)$ =2.7; p=.09), with a significant decrease of levelD values for the voiced fricatives only in the TH group (z= -2.6; p=.007). An interaction between chronological/auditory age group, auditory status and phoneme was observed ($\chi^2(15) = 25.4$; p = 0.04), with no chronological/auditory age group effect in the CI group, compared to decreased values in older children of the TH group for /f/, /s/, /ʃ/ and /z/. A CS exposure grouping effect ($\chi^2(2) = 7.3$; $p = .02$) as well as an interaction between CS grouping and phoneme were observed ($\chi^2(10) = 106.9$; $p<.001$). Indeed, levelD values were significantly higher in general in the CI/CS0 group compared to the TH group, and TH group had significantly higher values for the phoneme /s/ and /z/ compared to the other two groups. An elicitation type*CS exposure group interaction effect was also retrieved ($\chi^2(2)= 10.1$; $p=.006$), with higher values for CI/CS0 group for /f/ compared to CI/CS1 ($\chi^2(157) = 2.3$; $p=.06$) and TH group ($\chi^2(210)=1.9$; $p<.001$), with significantly lower values for /z/. CI/CS1 had lower values than the CI/CS0 group for /ʃ/ in the repetition condition ($\chi^2(231) = 2.6$; $p=.02$). An effect of age of implantation ($\chi^2(2) = 6.1$; $p = .04$) in interaction between group and phoneme type ($\chi^2(10) = 55.7$; $p < .001$) was observed. Specifically, the later implanted children showed significantly higher values than the TH children ($z = 2.45$; $p = .04$) for the phonemes /f/ and /s/.

3.3.3 Stop consonants

An interaction between auditory status group and voicing type (voiced vs. voiceless) was observed on the VOT of the stop consonants ($\chi^2(1) =30.58$; $p<.001$), with higher VOT for voiceless stops and lower for voiced stops in the TH group when compared to the CI group. Phoneme*group pairwise comparisons shown that this group effect was significant for the voiceless stop /t/ and the voiced /b/ and /d/ (see Figure 5.3).

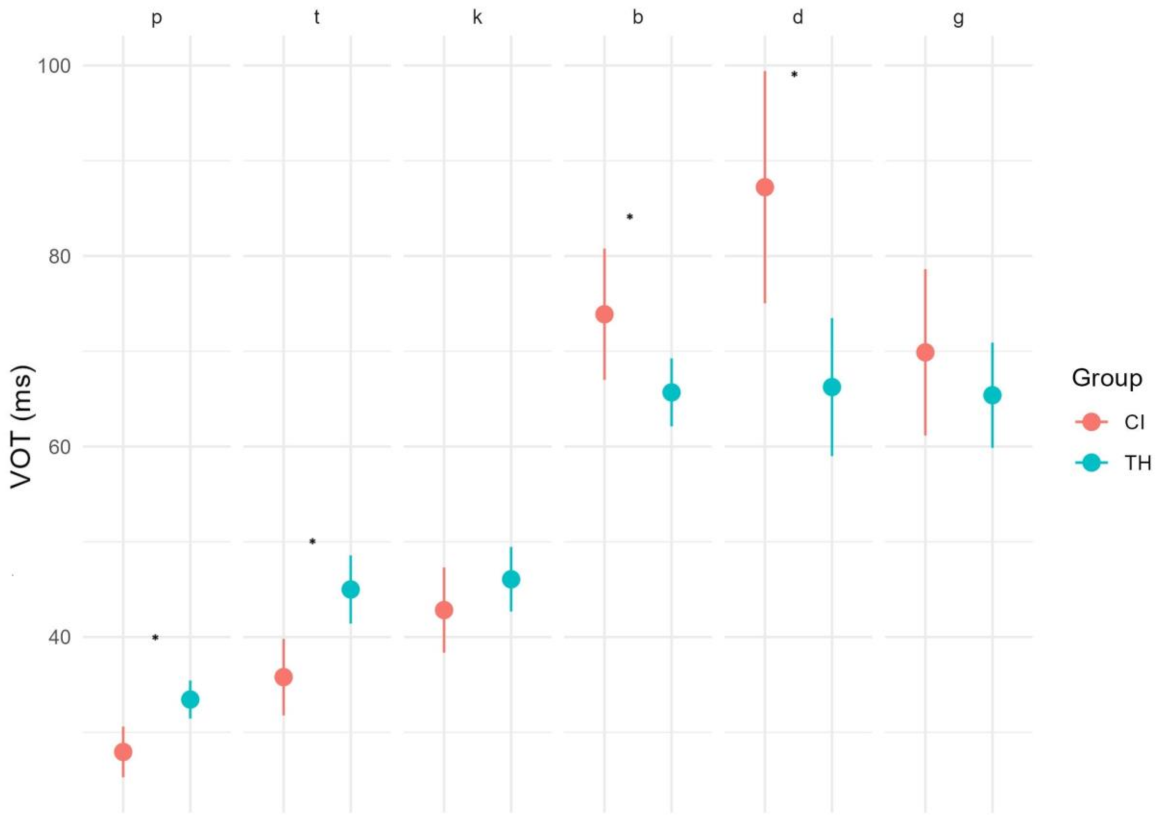

Figure 5.3: Means and 95% confidence intervals of the VOT values of the different voiced/voiceless stops among the CI and TH groups.

An elicitation type effect ($\chi^2(1)$ =6.4; p=.01) as well as an interaction between elicitation type, auditory status group and voicing type ($\chi^2(3)$ =39.6; p<.001) is observed. Indeed, VOT values are overall higher in the repetition condition, particularly for the voiceless stops, in the TH group (naming : 39.9ms – repetition : 46.9ms ; z=7-6.95; p=.02), and to a greater extent in the CI group (naming : 33.2ms – repetition : 43.8ms; z=-10.6; p=.001), allowing them to reach similar mean values than in the TH group. An interaction between chronological/auditory age group and auditory status group is observed ($\chi^2(10)$ =48.4; p<.001). Indeed, in the TH group, an increase of the mean values from younger to older age groups is observed for voiced and voiceless stops, while no (chronological or auditory) age effect is observed in the CI group. A CS exposure grouping*voicing type interaction is observed ($\chi^2(2)$=10.92; p=.004), with the CI/CS0 group showing higher VOT values for voiced stops compared to the CI/CS1 (t(68)=-0.015; p=.08) and TH groups (t(68)=-0.021; p=.002), whereas the CI/CS1 group shows the lowest VOT values for the voiceless stops (t(68)=-0.011; p=.003). Phoneme*CS grouping pairwise analysis reveals that the higher values in the CI/CS0 group is significant for voiced /b/ and /g/ compared to the other groups, while CI/CS1 children shows higher values for /d/ compared to TH children. The CI/CS1 group shows lower values than the TH group for voiceless /t/ and /k/. An interaction between CS exposure grouping, voicing type and elicitation type is also observed ($\chi^2(7)=40.9$; $p<.001$), with a significant increase of the voiceless stops VOT in the repetition condition in the CI/CS1 group (naming : 32ms - repetition : 42.3ms ; z=-2.6; p=.007), this increase being only marginal in the CI/CS0 group (naming : 36ms - repetition : 46ms ; z = -1.7 ; p=.08). An interaction effect is observed between age of implantation and voicing type in plosives ($\chi^2(2) = 34.5$; $p < .001$). Specifically, children in the late implantation group showed significantly longer negative VOT values than children in the TH group (z = 2.7; p = .02). An interaction effect appears between age of implantation and phoneme type ($\chi^2(10) = 47.5$; $p < .001$), with the lengthening of negative VOTs in the late implantation group being significant for the phonemes /b/ and /d/.

3.3.4 Multiple factor analysis of acoustic measures

A multiple factor analysis was conducted, integrating subject-averaged values of NAF and Euclidean distances in F1-F2-F3 plane between each nasal vowel and the averaged values of the associated oral vowels, the differences between positive and negative VOT values, as well as spectral peak values by location (/f/-/v/ - /s/-/z/ - /ʃ/-/ʒ/) and ampDiff and levelD mean values. These variables were grouped according to the type of segment characterized (fricative, stop, nasal/oral vowels) but also the production mechanism associated (place vs. frication noise for fricatives, formant vs. NAF values for vowels). Among the 8 dimensions generated, the first three will be analyzed, capturing 61.84% of the explained variance. The first dimension, contributing to explaining 28.5% of the total variance, is more correlated with groups of variables associated with fricative consonants (place = 0.79; frication = 0.62) and with spectral peak variables (SP /s/-/z/ = 0.79; SP /f/-/v/ = 0.78), while variables associated with frication quality are negatively correlated (levelD = -0.8, ampDiff = -0.44). In other words, positive values on the first dimension indicate high values of spectral peaks as well as lower values of levelD and ampDiff (indicating more reinforcement of high frequencies in the frication), while negative values indicate lower spectral peaks and higher values of levelD and ampDiff (enhancement of mid-range frequencies in the frication). The correlations between additional categorical variables and dimension 1 show that children in the CI group are negatively associated with the dimension (-0.63), whereas children in the TH group are positively associated with the dimension (0.93). The second dimension, contributing 21.5% of the total variance, is associated with the variable related to nasal/oral differences in terms of NAF values (0.47), with positive correlations associated with the NAF values mean differences (0.69), as well as with the variable associated with VOT values (0.54) and negatively with spectral peak of the posterior fricatives /ʃ/-/ʒ/ (-0.63). Positive values are then associated with greater nasal/oral distinction based on NAF values and greater voiced/voiceless VOT values distinction. An association is observed with categorical supplementary variables of chronological/auditory age group, with the older age group positively correlated with the dimension (0.66) and younger negatively correlated (-0.69). The third dimension, contributing 16.8% of the total variance, is associated with the variable related to nasal/oral differences in terms of F1-F2-F3 E.D. (0.63) with positive correlations associated with the of the F1-F2-F3 E.D. mean differences (0.79), but negatively with the variable associated with VOT values (-0.54). A link with chronological/auditory age group is observed, with the dimension being negatively correlated with the older chronological/auditory age group (-0.47).

Figure 5.4 illustrates the distribution of children from the CI and TH groups along dimensions 1 and 2 (left) and 1 and 3 (right), along with ellipses representing 95% confidence intervals around the group means. The ellipses of the two groups are primarily distinguished on dimension 1, with children from the TH group located on the positive side and CI on the negative side. This is consistent with the analyses on fricatives, showing a clear effect of auditory status on productions, with children in the CI group exhibiting lower spectral values, as well as higher levelD values indicating less utilization of high frequencies in their noise frication. On dimension 2, the group mean tends more towards positive values for the TH group and negative values for the CI group, while on dimension 3, both groups are close to 0. It is important to note the large variability around the ellipses. Note the contrasting situation between the two groups in the dimension 1/dimension2 plan: only children from the TH group are situated in the extreme right-hand quadrant (values greater than 1 in dimensions 1 and 2) and only children from the CI group in the extreme left-hand quadrant (values less than -1 in dimensions 1 and 2), testifying to contrasting profiles.

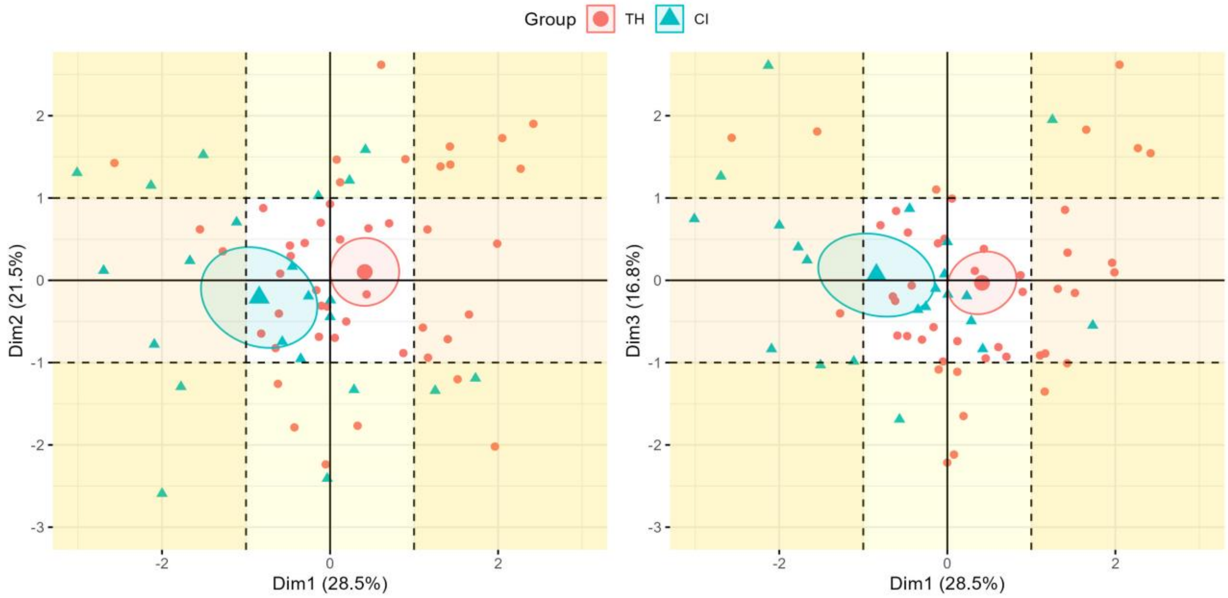

Figure 5.4: Scatter plot of statistical individuals based on dimensions 1 and 2 (left) and 1 and 3 (right) of the multiple factor analysis. Ellipses represent confidence intervals around the mean points of TH and CI groups.

Considering the other group variables, different trends between the CI/CS0 and CI/CS1 groups for dimensions 2 and 3 can be observed in Figure 5.5 (top graphs). Indeed, on dimension 2, the ellipse of CI/CS1 children tends more towards negative values, while the CS0 group leans towards around zero, with more variability. The CI/CS1 group tends to distinguish less nasal/oral vowels based on the NAF values. For dimension 3, the CI/CS1 group has average values towards positive values, showing less nasal/oral distinction based on F1-F2-F3 E.D. values, whereas the CI/CS0 group is situated in negative values with again a large variability. Considering the chronological age groups (middle graphs), we can see a trend for younger children to be positioned more to the right on dimension 1, in negative values on dimension 1, and positive on dimension 2. It seems that younger chronological age group 2;6-3;6 (age group represented only by children from the TH group) produce their fricatives with high spectral peaks with frication noise rich in high frequencies, while they mark the nasal/oral distinction more based on the oropharyngeal configuration (F1-F2-F3 E.D.) and less on nasal resonance. This effect is attenuated when considering auditory age, thus including children from the CI group within the 2;6-3;6 age group. When considering implantation age groups on dimension 1, early implanted children (CI/EI) have their average values intermediate between those of the late implantation group and (CI/LI) the TH group. It can also be seen that the CI/EI group is situated towards negative values on dimension 2, while the group with later implantation seems to be more situated towards positive values for dimension 3.

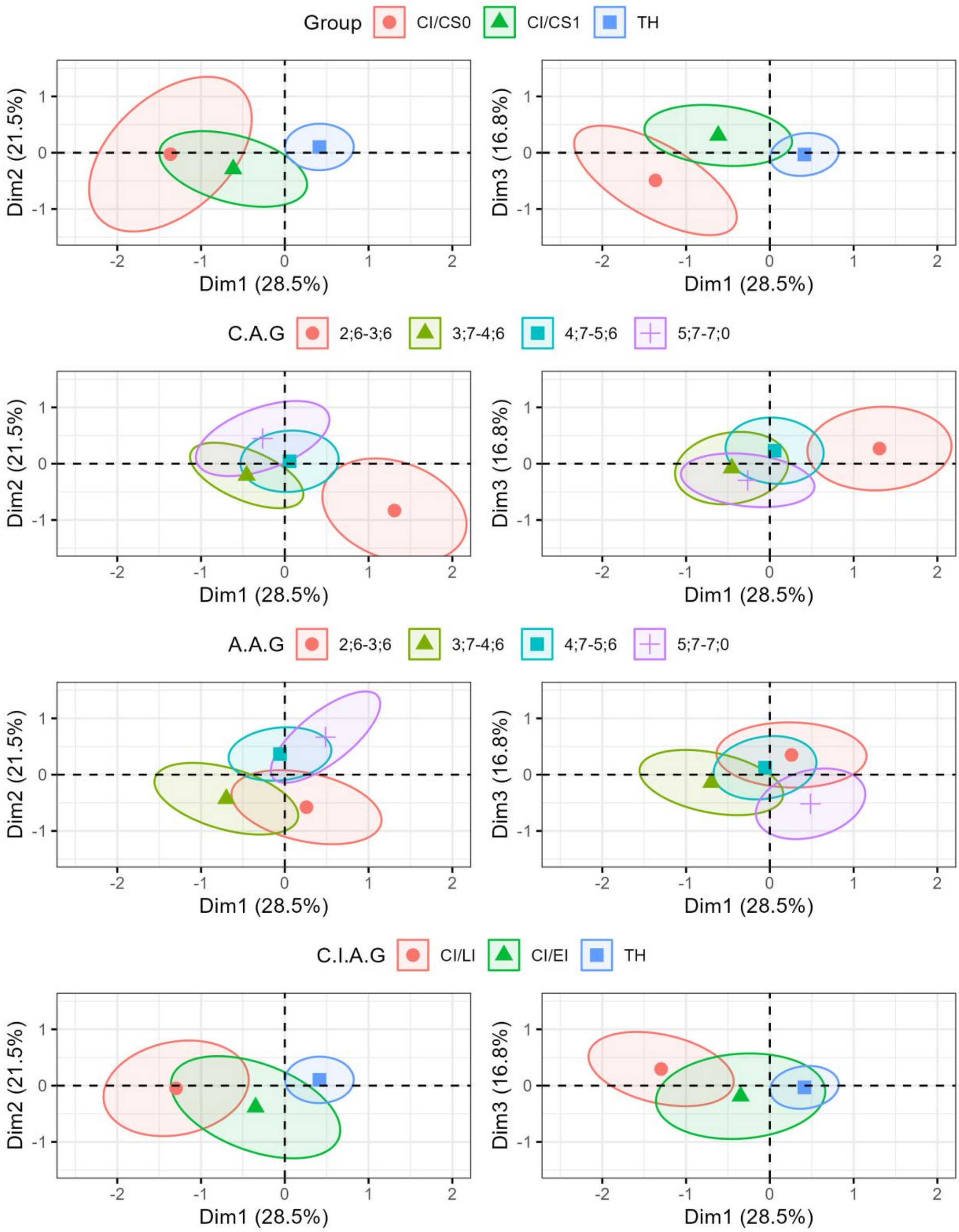

Figure 5.5: Individuals plot representing ellipses around the mean values of the groups based on exposure to CS (top graphs), chronological age (middle-top graph), auditory age (middle-bottom graphs), and age of implantation (bottom graphs), according to dimensions 1 and 2 (left side) and dimensions 1 and 3 (right side).

3.4 Link between phonological performance and acoustic dimensions.

The study of correlations between various phonological scores and error types with the three dimensions of multiple factor analysis has revealed moderate and significant correlations between dimension 2, related to the marking of nasal/oral distinctions by NAF values, and various phonological scores among the CI and TH groups (see Table 5.6).

Factor analysis dimension	Group	% correct phonemes (PCP)	% correct nasal vowel (PCN)	% correct fricatives (PCF)	% correct stops (PCS)	% vowel nasalization	% vowel denasalization	% voicing errors	% devoicing errors
1	CI	0,19	0,11	0,23	0,19	-0,006	-0,03	-0,44*	0,01
	TH	-0,07	-0,23	-0,17	-0,05	-0,02	0,21	0	0,35*
2	CI	0,45*	0,42*	0,46*	0,47*	-0,07	-0,18	-0,26	-0,33
	TH	0,46**	0,54***	0,54***	0,45**	-0,31**	-0,38**	0	-0,25
3	CI	0,11	0,2	0,06	0,07	-0,22	-0,18	0,15	0,11
	TH	0,05	0,18	0,03	0,08	-0,03	-0,11	0,19	0,047

Table 5.6: Correlations between phonology and acoustic analysis. Legend: ns, *p<.05, **p<.01, ***p<.001

In this regard, high values on the dimension, indicating a better nasal/oral distinction in terms of NAF as well as a better marking of the distinction between voiced and voiceless stops, are associated with better phonological performance. Among children in the TH group, it is also observed that dimension 2 is negatively correlated with the occurrence of errors in oral vowel nasalization and nasal vowel denasalization. A negative correlation between dimension 1 values and the number of voiced errors is observed in the CI group, while a positive correlation is observed in the TH group with the number of voiceless errors.

4. Discussion

The present study investigates the phonological and phonetic skills of a group of 23 children with cochlear implants (CI) and 47 children with typical hearing (TH) through the analysis of productions obtained with a naming task. Phonological skills are examined by assessing correct phoneme scores, while phonetic skills are studied through acoustic analysis of three types of segments: nasal and oral vowels, fricative consonants, and stop consonants. These segments have been chosen because each is primarily supported by rather contrasting acoustic cues, namely low-frequency cues, high-frequency cues, and temporal information, respectively. The effect of auditory status, as well as the effects of chronological/auditory age, exposure to Cued Speech, and age at implantation, are studied. Factor analyses were conducted on all acoustic variables, and the resulting dimensions were correlated with phonological scores.

4.1 Phonological form retrieval of the target words

It was hypothesized that, given the perceptual limitations of children with CI, their ability to retrieve the phonological form of their target words could be impacted, with repercussions both lexically (target word retrieval) and phonologically (accuracy of the retrieved phonological form). At the lexical level, children in the TH group demonstrated greater ease in retrieving target words, as evidenced by their significantly higher percentage of spontaneous naming (84%), as well as their higher percentage of retrieval based on phonological cueing. Children in the CI group showed lower percentages in spontaneous naming (77%) and relied more on repetition (18%). Semantic and phonological cueing provided little assistance in target retrieval, suggesting differences in lexical storage rather than access difficulties compared to their typically hearing peers, who benefited to a greater extent from phonological prompts. A considerable number of studies investigating lexical production in children with cochlear implants have shown comparable performances to typically hearing peers of the same chronological age (Caselli et al., 2012; Luckhurst et al., 2013) or when matched for auditory age (Duchesne et al., 2009) or in early implanted children (Connor et al., 2006; Maner-Idrissi et al., 2009; Manrique et al., 2004; Rinaldi et al., 2013). Other studies show more moderate lexical performances (Nittrouer et al., 2018; Young & Killen, 2002) or with clear difficulties identified (Cambra et al., 2021). Our results seem to align more with these studies, with significantly lower performance than those of children with typical hearing, without a positive effect of chronological, auditory age, or age of implantation. However, a beneficial effect of exposure to Cued Speech is observed, with performances among children exposed to Cued Speech reaching those of the TH group. These findings support literature that has highlighted a positive impact of Cued Speech on children with CIs, both for perceptual skills (Leybaert and LaSasso, 2010; Van Bogaert et al., 2023) and productive abilities (Machart et al., 2021). Studies have also shown a positive impact on early lexical development (Moreno-Torres & Torres, 2008; Rees & Bladel, 2013). Cued Speech, providing complete visual access to all distinctive features of speech sounds, may enable the child to develop more precise phonological representations and thus be more efficient in the storage and retrieval of lexical targets.

On the phonological level, lower performances are also observed in children in the CI group for all types of targeted phonemes: fricatives, nasals, and stops. Certain types of errors were predominantly found in children in the CI group, such as voicing errors, denasalization of nasal vowels, stopping, or fricativization. While stopping errors have been previously reported in children with moderate (Teveny & Yamaguchi, 2023) and profound deafness (Baudonck et al., 2010), and can be classified, along with denasalization errors, as typical errors in development according to Jakobson's markedness theory (Jakobson, 1968), voicing and fricativization errors suggest a more atypical developmental profile. Furthermore, we did not find any effects of chronological/auditory age or age of implantation on phonological scores and error patterns, suggesting more an effect of auditory status than developmental delay. These results support the notion of phonological development constrained by the limitations of the CI described previously, which may lead to underspecified phonological representations and consequently result in production errors. Within this study, this proposition is supported by the observation of a positive effect of exposure to Cued Speech on performances, although scores of CS1 group do not reach the levels of typically hearing children. The group exposed to CS also made fewer errors of oral vowels nasalization, which is consistent with previous studies on vowel nasality perception (Fagniart et al., 2024a) and production (Fagniart et al., in press), as well as fewer errors of fricativization, indicating greater stability of phonological representations regarding manner of articulation.

4.2 Nasal-oral vowels distinction

The acoustic analyses characterizing the distinction between nasal and oral vowels reveal an increased marking of the nasal/oral contrast based on indices related to oropharyngeal configuration (formant values) in the CI group compared to TH group. This result is consistent with previous findings obtained in a pseudoword repetition task and supports the hypothesis that CI children may be more inclined to employ perceptually salient acoustic cues both in perception and production (Fagniart et al., 2024, in press). However, the results showed lower values of NAF, representing the degree of nasalization predicted based on a series of acoustic indices related to nasal resonance, suggesting a lesser exploitation of nasal resonance through velopharyngeal opening to distinguish nasal and oral vowels. As described in section 1, indices related to nasal resonance, primarily carried by low-frequency information associated with fine spectral resolution, are more likely to be poorly transmitted by the CI. This could explain the difficulties observed in phonological production (percentage of correct nasals and (de)nasalization errors), as already noted in the literature on nasal/oral vowel perception (Bouton et al., 2012; Borel, 2015; Borel et al., 2019; Fagniart et al., 2024a). These perceptual difficulties may therefore lead to atypically specified phonological representations (marking related more to visually accessible cues such as information related to oropharyngeal configuration), thus resulting in these atypical productions compared to hearing peers. Children exposed to CS exhibit the lowest values in terms of NAF, suggesting a productive profile even more reliant on a phonological system constructed around the most salient cues to access the distinctive features of their oral language. Specifically, in the case of nasal vowels, this relies more on oropharyngeal configurations at the expense of cues related to nasal resonance. The comparison of productions according to the type of elicitation (spontaneous naming or repetition of the target word) supports these findings. Indeed, while children in the TH group improve the marking of nasal-oral distinction in repetition condition for both types of cues as well as NAF values, children in the CI group see their values increase only for the F1-F2-F3 E.D. cue, and on the contrary, their NAF values decrease. In perception, they thus seem to be able to correctly exploit visually accessible information (lip rounding, mouth opening) but not the information related to velopharyngeal opening.

4.3 Fricatives production

Regarding the acoustic study of fricatives, the results confirmed various findings already reported in the literature. Indeed, lower acoustic values had been observed for the center of gravity of fricatives in children with CI (Yang and Xu, 2023), as well as in French-speaking children (Grandon and Vilain, 2020). However, these studies had been limited to the investigation of fricatives /s/-/z/ or all voiceless fricatives in French (/f/,/s/,/ʃ/), and this observation is here extended to voiced segments. The differences between groups were significantly observed for the phonemes /f/, /s/, and /z/, whose spectral peaks are on average higher than those of segments /ʃ/ and /ʒ/, characterized by lower values. This is entirely consistent with the acoustic limitations in high frequencies mentioned previously. These lowered thresholds also result in a lack of distinction among the three places of articulation among children in the CI group, as the peaks of the segments /f,v/, /s,z/, and /ʃ, ʒ/ are not significantly different. An effect of CS is observed to produce /f/ and marginally for /ʃ/, with values for the CI/CS1 group approaching those of the TH group. However, it is noteworthy that the distinction between the three places of articulation is still not significant in this group. Unlike the productive skills of nasal vowels, the contribution of CS is only moderate for the distinct production of the places of articulation of fricatives. The use of manual cues to provide visual support during the perception of fricative segments may not be enough to develop sufficiently specified representations. It is possible that the acoustic limitations for this distinction are too significant to be compensated for using CS, or that these segments, being among the last to be acquired in the development of children with typical hearing, may be even more challenging for children with CIs. To our knowledge, there is no study documenting fricative productions in terms of frication noise among CI users. The results of the present study show a clear tendency in the CI group to express frication by exploiting energy in mid-range frequencies and less in high frequencies, unlike children with typical hearing. This trend could also directly result from the perceptual limitations of the implant, restricting the perception of frequency ranges above approximately 8000 Hz. Indeed, the quality of fricative noise can only be perceived auditorily, with no visual/temporal cues supporting this type of production. This is supported by the study of values in the repetition condition: while TH children see improvements in their productions during repetition (increased spectral peaks, increased energy in high frequency resulting in decreased levelD values), children with CIs, on the contrary, experience slight deterioration in their productions (lower spectral peaks, increased levelD values). The perceptual limitations of CIs do not allow them to access the acoustic information related to the characteristics of fricative segments, thus preventing them from benefiting from repetition for these segments. Possible difficulties in adequately perceiving characteristics related to fricative sound could explain the higher occurrence of errors in articulation mode for stopping or fricativization errors observed in the study, and more broadly in the literature among individuals with moderate (Teveny and Yamaguchi, 2023) or severe deafness (Baudonck et al., 2010). However, an effect of the age of implantation on levelD values was observed, with higher values (and thus less reinforcement in high frequencies) in children with late implantation. It is therefore possible that early implantation allows, to some extent, better exploitation of high-frequency information, despite the technical limitations of the implant, due to the stimulation provided during the sensitive periods of the development of auditory cortical areas.

4.4 Voiced/voiceless stops production

Regarding the production of the voicing feature of stop consonants, a differentiated group effect is observed depending on the type of segments. Indeed, for voiceless consonants, there is a shortening of VOT values in the CI group compared to the TH group, which is congruent with the literature (Uchanski and Geers, 2003; Horga and Liker, 2006; Grandon et al., 2017). However, in Grandon's study (Grandon et al., 2017) on French-speaking children, only the phoneme /k/ showed a significant shortening in the CI group, whereas in the present study, it is precisely the phonemes /p/ and /t/ that are significantly shorter in terms of VOT. Grandon had suggested that obtaining a difference only on the phoneme /k/ could be attributed to a difficulty in coordinating the articulatory gesture, as /k/ has the longest positive VOT in canonical production. However, it is noteworthy that the children in Grandon's study were in a higher age range (6;6- 10;6). This difference may explain why, within the TH group, the productions were not sufficiently differentiated between the places of articulation of the voiceless segments, as the average positive VOT of /k/ (45ms) differed little from /t/ (44ms). As a result, the results did not show differences between the CI and TH groups for this phoneme, but rather for the more anterior phonemes /p/ and /t/, whose values were significantly lower in the CI group. Children in the CI group seem to have difficulty coordinating the articulatory gestures associated with the production of voiced stops in a picture naming task. However, when these segments are to be produced in repetition, children in the CI group produce the segments with elongation, allowing them to reach values similar to those of children in the TH group: thus, they are capable of effectively exploiting the acoustic information related to VOT to adjust their productions. On the other hand, for voiced segments, it is the TH group that exhibits a shortening of VOT values, for the phonemes /b/ and /d/. The study of the effects of exposure to CS showed that it mainly involves an elongation of VOT values found among children in the CI/CS1 group. It is possible that relying on temporal cues is a more prevalent strategy in the CI/CS0 group.

4.5 Acoustic profiles

The factorial analyses revealed two distinct trends in the productive profiles of the three investigated segments. Firstly, Dimension 1, which discriminates children well according to their auditory status, consisted of variables related to the quality of fricative production, both in terms of spectral peak and in terms of the utilization of high-frequency energy in frication. It was observed that children in the TH group were predominantly situated on the positive values on the dimension 1, indicating fricatives with high average spectral peak values, and frication noise containing a higher concentration of high frequencies. Dimension 2, on the other hand, was mainly associated with marking the nasal/oral distinction in terms of NAF values, but also, to a lesser extent, with the distinction between voiced and voiceless stop consonants. It is quite interesting to note that among children in both groups, positive correlations are observed between the values on this dimension and various phonological scores. Better marking of the nasal/oral distinction in terms of nasal resonance thus seems to be associated with better phonological performances, both among TH and CI children. Therefore, despite significantly lower NAF values among CI children, there seems to be some variability in the exploitation of nasal resonance cues, which may contribute to part of the variability in linguistic outcomes. In this regard, it is more surprising to see that Dimension 3, more associated with marking vowel nasality through cues related to oropharyngeal configuration (E.D. F1-F2-F3), is not positively correlated with phonological scores in the CI group. One might have expected that this marking strategy, reflecting a greater reliance on information assumed to be better coded by the CI, would be beneficial phonologically overall. In the study by (Fagniart et al., in press) the use of this strategy was associated with better intelligibility of nasal and oral segments. This study seems to indicate that this improvement in segment production is not necessarily associated with better phonological performances overall. These findings support the notion that while the perception-production of fricatives remains critical among the CI population, despite aids such as CS, the perception/production of nasal/oral vowels and stops entails significant variability, which may indicate possible compensations of the perceptual system in children with CIs. These findings are important to consider in the management and evaluation of language skills in children with CIs, to refine auditory stimulation techniques more based on perceptual skills accessible through the CI for critical segments, such as nasal vowels, and to quickly diagnose difficulties that may manifest subclinically.

The various findings of this study must be viewed considering certain limitations. Indeed, it is challenging to assemble a sizable sample with homogeneous characteristics among children with CIs, which complicates the generalization of results. Nevertheless, the results presented here are largely supported by existing literature and can therefore be taken seriously. Regarding the acoustic analyses, it should be noted that the target words were selected to create a list with frequent words, easily imaginable, and with low age of acquisition. These constraints did not allow for controlling various elements, such as phonemic neighborhood or overall syllabic context. Protocols targeting specific segments, with better control over parameters influencing the acoustic characteristics of productions, could be developed to address this bias in future investigations.

5 Conclusion

This study aimed to investigate and correlate phonological and phonetic skills through the analysis of picture naming tasks among children with CIs and their hearing peers. The following observations can be highlighted:

- Children in the CI group exhibit more difficulties in lexical and phonological domains, which may be compensated for by exposure to Cued Speech.
- CI users can exploit visually accessible information (such as oropharyngeal configuration) or information better coded by the CI to compensate for their perceptual difficulties, as noted in the production of nasal/oral vowels or voiced/voiceless stops, particularly among children using CS.
- Distinctive features relying on information not accessible through the implant and less compensable visually and/or temporally, such as the distinction of fricative consonants, are critical among CI children.
- Adequate exploitation of nasal resonance in distinguishing nasal/oral vowels is associated with better phonological performances.

These findings emphasize the perceptual system's ability to adapt and compensate for the limitations of CIs, a phenomenon that should be prioritized in children's management. Segments most at risk, such as fricative consonants, warrant particular attention to avoid significant phonological underspecification and associated linguistic delays.

Chapter 6 Lexical, morphological and morphosyntactic skills

After focusing on the production skills of different types of phonetic segments, the present chapter now aims to study the phonological, lexical, and morphosyntactic skills within the sample of children from the second data collection. However, for this article, which specifically examines group effects between children with cochlear implants (CI) and children with typical hearing, 4 children with CIs were excluded due to family bilingualism. Although these children have French as their first language, exposure to a second language in the family context could interfere with their linguistic skills and bias the group comparisons, as only monolingual children constitute the group of children with typical hearing. Therefore, the study focuses on a subgroup of 19 children with CIs compared to 47 children with typical hearing. The results from a picture-naming task, as well as the analysis of narrative productions by the children, are examined to extract developmental scores at the phonological, lexical, and morphosyntactic levels, which are then described and analyzed in relation to one another.

As the manuscript of this thesis is being finalized, this study is about to be submitted to the journal Frontiers in Human Neuroscience.

Abstract

Introduction: Significant variability in the language performance of children with CI is widely recognized in the literature, particularly concerning morphosyntactic (MS) skills. The perceptual limitations of the CI, which can lead to phonological difficulties, may be responsible for this increased vulnerability in grammatical abilities. In this context, the present study focuses on the morphophonemic processing of items distinguished by nasal and oral vowels in the French language - the feature of vowel nasality being known as challenging for

the CI population. Links between these performances and phonological and grammatical production skills will also be explored.
Method: Nineteen children with cochlear implants (CI) and forty-seven children with typical hearing (TH) were assessed for phonological skills through a picture-naming task, perceptual skills through a task involving the sentence/word-picture matching task with word target containing nasal versus oral vowels, and morpho-syntactic production skills through narrative productions. Various measures of linguistic complexity (MLU, verbs/utterances) and lexical diversity (D index) were evaluated among our groups and linked to perceptual and productive phonological performances. Chronological/auditory age, the timing of implantation, exposure to Cued Speech (CS), and the socio-economic status of the parents were also studied.
Results: Specific difficulties in processing items distinguished by nasal and oral vowels were observed among the children with CI, as well as lower performance in narrative production, as reflected in MLU, verbs/utterances ratio, and the occurrence of complex function words or verb tenses, as well as in the lexical diversity index. Specific links were observed between phonological and morphosyntactic components among the children with CI in correlational analyses. Different performance profiles were observed, which could be linked to the significant variability reported in the literature.
Conclusions: The perceptual limitations of the CI have a significant impact on the linguistic development of children with CI, with various sources of variability as well as possibilities for compensation, notably through the use of multimodal speech perception stimulation methods such as CS.

Keywords: morphosyntactic skills, lexical skills, language development, cochlear implants

1. Introduction

The development of language in prelingually deaf children with unilateral or bilateral cochlear implants (CIs) has been the subject of numerous investigations in recent decades. One element is widely agreed upon among researchers: the performance of children with CIs is extremely variable. Some children reach the level of their typically hearing (TH) peers, while others display delayed or even atypical profiles. This variability in performance is not equally distributed across language components: difficulties are most frequently reported in the phonological (Bouton et al., 2012; David et al., 2021; Nittrouer et al., 2018) and morpho-syntactic (MS) components (Caselli et al., 2012; Duchesne et al., 2009; Le Normand & Thai-Van, 2023; Rinaldi et al., 2013). Indeed, despite the undeniable benefits of the cochlear implantation in auditory perception and in promoting the emergence of spoken language, the cochlear implant does not transmit the sound signal with the same precision as typical hearing. The sound transmitted by the implant is particularly limited in its spectral resolution and can be imprecise in certain frequency ranges, impacting the processing of some segmental and supra-segmental aspects of speech. Furthermore, the period of auditory deprivation before implantation can lead to a lack of stimulation of the auditory pathways during sensitive periods of the development of auditory brain areas. These factors can affect certain language components more severely. The aim of the present study is to examine the phonological and morphosyntactic skills of French-speaking children with CIs compared to their typically hearing peers. The study will particularly focus on vowel nasality, a distinctive feature of the French phonological system that supports several grammatical marks and has been recognized in the literature as being vulnerable to perception difficulties in both adults and children with CIs.

1.1. Grammatical skills in children with CI(s)

Despite the undeniable benefits of cochlear implantation on the linguistic development of deaf children, morphosyntactic (MS) development remains an area of language subject to persistent difficulties in this population. Indeed, lower performances are reported in formal tests evaluating perceptive and productive skills (Bourdin et al., 2016; Caselli et al., 2012; Duchesne et al., 2009; Schorr et al., 2005; Young & Killen, 2002). Linguistic corpus analyses have shown lower values in linguistic development cues such as MLU (Mean Length of Utterance) and/or difficulties in the use of free and bound grammatical morphemes (Hansson et al., 2017; Majorano et al., 2024; Nittrouer et al., 2018; Szagun, 2001). The emergence of function words in the early development of grammar does not follow the same course as in typically hearing children, with greater difficulties in producing complex, less salient, unstressed function words such as pronouns (subject, object, relative), possessive and modal verbs or prepositions. It is suggested that CI users tend to store lexical representations more than phonological ones (Le Normand & Moreno-Torres, 2014), facilitating the acquisition of content words such as nouns or main verbs over function words (Le Normand, 2004; Le Normand & Thai-Van, 2023). Studies that have jointly examined lexical and morphosyntactic components in the same children with CI have shown disparities in performance levels. Indeed, lexical development often appears to be more equivalent to that of peers with typical hearing (Caselli et al., 2012; Duchesne et al., 2009; Rinaldi et al., 2013), with some authors observing a one-year gap between lexical and morphosyntactic development (Le Normand & Moreno-Torres, 2014). This gap is suggested to be due to the greater prominence of lexical elements in spoken language compared to grammatical words. Moreover, morphological and syntactic variations are more complex to teach/learn formally than vocabulary words (Hage, 2005).

While these difficulties are evident when children with CIs are studied as a group, the study of individual profiles shows substantial variability. Indeed, some studies report performances equivalent to those of typically hearing peers for about 50% of the children matched by chronological age (Geers et al., 2003), auditory age (Guo & Spencer, 2017), or vocabulary size (Jung & Ertmer, 2018). Different inter-individual variability factors can contribute to a certain degree of variability in performance. The effect of auditory age, defined as the age from exposure to auditory stimulation through a CI, has been regularly tested on linguistic components, with contrasting findings depending on the studies. While various authors observe significantly improved linguistic performances with advancing auditory age (Caselli et al., 2012; Flipsen & Kangas, 2014; Nicholas & Geers, 2007; Szagun, 2004a; Wie, 2010), others do not report any influence of auditory age (Duchesne et al., 2009; Hess et al., 2014; Rinaldi et al., 2013). The role of parental socio-economic status (SES), often assessed through parental education, remains a topic of debate. Some studies have found significant associations between family SES and linguistic outcomes (Geers et al., 2009; Huber & Kipman, 2012; Szagun & Stumper, 2012) or grammatical development (Le Normand & Moreno-Torres, 2014). However, other research has found no significant links between SES and these linguistic measures (Moreno-Torres et al., 2016). Different elements can contribute to an effect of parental education : high-SES mothers has been observed to tend to speak more and with greater syntactic complexity (Huttenlocher et al., 2002; Vasilyeva et al., 2008) or with a more frequent use of certain parental language facilitation strategies, such as expansion (Szagun & Stumper, 2012). However, a recent meta-analysis on the role of various elements of the family environment highlights the positive impact of parental input during the early years of life, with more heterogeneous effects concerning the level of parental education (Holzinger et al., 2020). Language stimulation modes can also contribute to variability in children’s performances. While several studies highlight the importance of stimulating oral language through an oral-only communication mode, compared to communication that combines oral language and sign language - formerly referred to as total communication (Dunn et al., 2014; Geers et al., 2003; Meyer et al., 1998; Niparko et al., s. d.; Peterson et al., 2010) - recent studies outline the benefits of introducing oral/sign language bilingualism to expose the child to a fully accessible communication system as early as possible (Delcenserie et al., 2024). Different methods of language rehabilitation can impact language development: in this regard, Cued Speech (Cornett, 1967) is a manual code used in addition to spoken language to supplement lip-reading, making all the phonological contrasts of an oral language visually accessible. The benefits of its integration into the care of children with CIs have been recognized in speech perception (Bouton et al., 2011; Leybaert & LaSasso, 2010; Van Bogaert et al., 2023) and speech production (Machart et al., 2024), as well as in morphosyntactic production (Hawes, 2004). Among others, these various individual and environmental characteristics have been identified as potential sources of variability, but none can clearly explain the disparities in performance or predict whether a child with a CI will achieve performances equivalent to those of hearing peers. Note that some authors have also observed MS performance in children with CI that is comparable to that of children with specific language impairment (SLI) (Benassi et al., 2021; Bourdin et al., 2016; Majorano et al., 2024), suggesting atypical language development.

1.2. Relationship between processing limitations and grammatical development

Despite the constant evolution of sound coding devices, cochlear implants are still incapable of completely coding and transmitting the auditory signal, as the fine acoustic details are often too complex to be processed by even the most recent devices (for a description of the sources of degraded performance in speech sound coding via the implant, see Başkent et al., 2016) . This limitation impacts the quality of the phonological representations in prelingually deaf children, which directly affects their phonological skills as well as their overall linguistic skills, particularly their grammatical skills.

The increased vulnerability of morphosyntactic skills in cases of perceptual and/or phonological limitations has been explained by various models developed to explain SLI, where these skills are most severely affected (Parisse & Maillart, 2007). For instance, the surface hypothesis (Leonard et al., 1992) suggests that grammatical morphemes are more vulnerable due to their typical final positions and placement in unstressed syllables. The cognitive operation of attributing a grammatical mark is also complex, making these morphemes more likely to be processed imprecisely, impacting grammatical development in both perception and production. Joanisse & Seidenberg (1998) propose a theoretical model that also emphasizes the lack of perceptual salience of morphological markers, adding that the root cause of difficulties lies initially in perceptual issues. This leads to difficulties in perceiving and categorizing phonological contrasts of the language and results in underspecified phonological representations. Since morphosyntactic markers primarily rely on contrasts between morphophonological forms, they are likely to be problematic in this context. The mapping hypothesis (Chiat, 2001) complements these propositions by postulating that developmental language disorders are related to a deficit in mapping between a phonological form and its concept/referent, which can then affect lexical and morphosyntactic development. However, lexical and morphosyntactic items do not hold the same value in terms of conceptual representation: concepts associated with lexical item are more frequently linked to visual, social, or emotional cues, unlike grammatical marks which rely solely on phonological cues from the spoken chain. According to this model, grammatical words are more vulnerable than nouns, and a concreteness effect can affect all classes of words.

In the case of children with hearing loss, the limitation and/or degradation of auditory input, causing a perceptual deficit, will be even more pronounced on these less salient and more abstract elements of the language, such as grammatical morphemes. This could explain why the morphosyntactic level is most often deficient compared to the lexical level in this population (Caselli et al., 2012; Duchesne et al., 2009; Le Normand & Moreno-Torres, 2014; Rinaldi et al., 2013), with lexical items benefiting from greater salience and concreteness effects. This could be corroborated by the study of Hansson et al. (2017) which found a strong link between the level of phonological development, assessed through a non-word repetition task, and skills in sentence comprehension as well as grammatical accuracy, evaluated through narrative production in children with CIs aged 5 to 9 years. The authors attributed these difficulties to imprecise phonological representations due to degraded auditory input, impacting the processing of grammatical morphemes both in processing and morphosyntactic production. In the same vein, an interesting pilot study found improvement in morphosyntactic development among children benefiting from intensive exposure to CS (Hawes, 2004). The author suggested that perceptual deficits could be mitigated by providing more complete audiovisual information, emphasizing the less salient elements of language, such as grammatical morphemes, through the use of CS.

The perceptual limitations of CI are likely to cause difficulties not only at the segmental level but also at the suprasegmental level, which can also contribute to MS difficulties. Indeed, it has been observed that the CI population experiences difficulties in correctly processing information related to F0 frequency and its variations, causing challenges in identifying emotions based on prosody (Chatterjee et al., 2015, 2023; Everhardt et al., 2020; Richter & Chatterjee, 2021) or difficulties in musical processing (Steel et al., 2020). Suprasegmental elements of language are known to be crucial in early language development and are considered a prerequisite for MS development in typically hearing children through prosodic bootstrapping. Various studies have thus proposed that MS difficulties in children with CI may be prosodic, particularly in studies focusing on the acquisition of determiners. Indeed, various studies have shown difficulties in the acquisition of this type of function words (Hilaire et al., 2002; Majorano et al., 2024; Moreno-Torres & Torres, 2008; Szagun, 2004b). This vulnerability in acquiring determiners is entirely consistent with the previously mentioned perceptual limitations, related to the lower perceptual and conceptual salience of these function words, but also with an atypical development of prosodic representations. However, this latter hypothesis has not been verified in French: a study by Le Normand demonstrated that children with CIs do benefit from prosodic bootstrapping (Le Normand & Moreno-Torres, 2014). The author observed more omissions of determiners before bisyllabic words than monosyllabic ones, indicating sensitivity to the dominant iambic metric structure in French consistent with what is observed in typically hearing children (Demuth & Tremblay, 2008). Although difficulties seem to be present in processing F0 variations, it appears that children with CIs are still able to use rhythmic information from the language to perceive its metric structure.

These various elements from the literature provide a partially explanatory framework for the increased difficulties potentially encountered by children with CI in MS development. Difficulties in processing certain speech sounds as well as suprasegmental acoustic features supporting prosodic patterns are likely to affect the acquisition of grammatical morphemes. The present study will particularly focus on the nasality feature in French vowels.

1.3. Speech sound processing: focus on nasality feature in French

The difficulties in the processing of speech sounds by CI users affect more severely certain phonological features carried by acoustic cues less precisely coded by the CI (Bouton et al., 2012; Cheng et al., 2021; Moon & Hong, 2014; Peng et al., 2019). This is particularly the case for the place of articulation of consonants and especially fricative consonants, as well as the nasality feature in French vowels. In French, as in approximately 20% of the world's languages (Borel, 2015), nasality is a distinctive feature of the vocalic system. The [nasal] vs. [oral] specification allows for the distinction of minimal pairs at the lexical level, but also morphophonological oppositions that serve as grammatical markers.

However, vowel nasality is carried by fine acoustic cues that require optimal spectral resolution processing skills, which is precisely problematic in the processing of the sound signal by the CI. Various experimental studies have thus shown difficulties in the identification and discrimination of nasal and oral vowels in both children and adults with CI(s) (Borel, 2015; Borel et al., 2019; Bouton et al., 2012; Fagniart et al., 2024a). CI users tend to have difficulty distinguishing a nasal vowel from a close oral counterpart in terms of oropharyngeal configuration. Their perceptual difficulties, mainly concerning the processing of the nasal quality of the vowel, so that the identification/discrimination of nasal and oral vowels is primarily carried out through the exploitation of cues better coded by the CI, such as formant frequencies. These perceptual difficulties manifest in specific productive profiles. Indeed, children with CIs judged to be the most intelligible are those who distinguish nasal and oral vowels using acoustic cues related to oropharyngeal configuration (formant frequencies) and length differences rather than presence or absence of nasal resonance (Fagniart et al., in press).

High variability in performance is notable in the above-mentioned studies, with significantly higher performance among children who have integrated CS early and intensively into their care and family context. It is thus assumed that CI children are capable of compensating for their perceptual difficulties related to sound processing by the CI through the activation of multimodal speech perception mechanisms, exploiting visual cues related to lip-reading and the manual cues of CS in addition to the incomplete sound signal. This variability in performance is also observed in the use of the acoustic cues associated with nasal resonance: some children seem to control the nasal/oral quality of their productions more adequately, and this ability has also been shown to correlate with phonological development (Fagniart et al., 2024b).

1.4. The present study

Through a review of the scientific literature, it has been observed that many studies report increased vulnerability in the development of morphosyntactic skills among children with CIs. While most authors agree that the perceptual limitations of the sound transmitted by the CI, combined with delayed access to oral input, are primarily responsible for these children's difficulties, some authors emphasize the effect of specific individual and/or environmental, which can explain part of the performance variability.

The objective of the present work is to delve deeper into the phonological hypothesis of morphosyntactic difficulties in children with CIs, under the assumption that the acoustic limitations related to sound processing by the CI lead to imprecisions in phonological processing, thereby impacting linguistic abilities. The variability in speech sound processing skills, linked on one hand to the etiological characteristics of deafness, anatomical peculiarities and surgical conditions of the implantation, and on the other hand, to the variability in the use of strategies to compensate for initial difficulties, could help explain, at least partially, the variability in linguistic performance. Grammatical competence is particularly vulnerable in this regard due to the lower salience of grammatical morphemes in spoken language and, in French, the richness of morphophonological processes that convey grammatical markers (Le Normand & Thai-Van, 2023).

In this context, we have chosen to study more precisely the processing skills of different morphemic oppositions in grammatical contexts and lexical contexts (minimal pairs), as well as morphosyntactic production skills and their links with phonological skills in groups of children with cochlear implants and their typically-hearing peers. Morphemic oppositions involving the feature of vowel nasality are targeted. Indeed, it has been shown that the nasal vowel feature is poorly perceived among the CI population, leading to difficulties in discrimination and particularities in production, but with possible compensation strategies and notable variability. The opposition between nasal and oral vowels is part of the phonological mechanisms underlying certain grammatical oppositions in French, such as grammatical number in /il va/ *("he goes")* vs. /il vɔ̃/ ("*they go*").

First, a customized comprehension task designed at studying morphophonological processing will be introduced. The inclusion of different types of morphophonological oppositions, some of which being based on vowel nasality, will allow us to assess the impact of perceptual difficulties on morphological processing skills in different grammatical (gender and number marking) and lexical (minimal pairs) contexts. The various scores obtained from this comprehension task will also be linked to different morphosyntactic production scores obtained through narrative production, in order to study the connections between potential morphological processing difficulties and grammatical skills within the two groups of children. The link between performance in morphological processing and MS production will be studied in connection with the level of phonological development of the children, assessed through a picture-naming task. Attention will also be given to the suprasegmental elements that may influence MS skills. Indeed, it has been shown that in French, determiners are more easily acquired before monosyllabic words than bisyllabic words, indicating a sensitivity to the predominantly two-foot rhythmic structure of French. A previous study (Le Normand & Thai-Van, 2023) confirmed that French-speaking children with CI(s) exhibit similar profiles, indicating a prosodic bootstrapping mechanism equivalent to that of typically hearing (TH) children. These findings will be re-examined in the present study and correlated with the productive MS skills of the children. Finally, building on the findings from the literature regarding the impact of environmental factors on linguistic development in general and morphosyntax in particular, the effect of different individual and environmental variables on MS skills will be studied.

Several objectives are pursued:

- To document the skills in morphological processing skills in grammatical and lexical contexts. We hypothesize that phrases distinguished by the nasal vowel feature will cause greater difficulties for children with CI;
- To document grammatical production skills through the analysis of narratives. Similar studies have already been conducted in French with younger children (Le Normand, 2004; Le Normand & Thai-Van, 2023), highlighting an atypical acquisition trajectory of function words in young children with CI compared to children with typical hearing. This study will focus on children from older age groups and aim to document performance in morphosyntactic production, the production of various function words and

different tenses of conjugation, as well as several types of grammatical errors among the groups of children. In particular, attention will be given to omissions of determiners before monosyllabic or bisyllabic words in order to study the children's sensitivity to the prosodic characteristics of French;

- To study the role of different variables proposed as contributing to morphosyntactic development and to the variability of performances observed among CI users in the literature. These variables include the level of phonological development, the level of maturation through the study of chronological and auditory age effects, as well as environmental variables such as parents' socioeconomic status and the level of Cued Speech exposure. The level of lexical development and its links with grammatical skills will also be examined in order to distinguish between overall effects of linguistic development and specific relationships among certain components.

2. Method

2.1. Participants

A group of children with typical hearing (TH group) and a group of children with cochlear implants (CI group) participated in the study. The TH group consisted of 47 French-speaking children with typical hearing, with an average age of 56 ± 7 months, who did not exhibit any learning delays or auditory disorders. The CI group comprised 19 French-speaking children (mean chronological age: 64 ± 2 months) with congenital bilateral profound hearing loss, 18 of whom had bilateral implants and one child with a unilateral implant. All CI participants received oralist auditory rehabilitation, both at their rehabilitation center and in their family environment. This group was further divided based on their exposure to Cued Speech: 7 children were not exposed to CS (CS0 group), 5 were occasionally exposed during speech therapy sessions (CS- group), while 7 were exposed early in their development and intensively, both in speech therapy and in their family context (CS+ group). Implantation age groups were also created: children who received their first implant before 18 months were considered early implantations (CI/EI, n=12), and those implanted after 18 months were considered late implantations (CI/LI, n=7). This criterion was selected to align with various studies showing significant benefits from implantation before 18 months (Sharma et al., 2020).

Subject	Sex	Chronological age (years ; months)	Age at first implantation (months)	Implantation age group: early (EI) – late (LI)	Auditory age group	Implantation type	CS exposure group	SES level
CI1	M	4;6	9	EI	3;7-4;6 y	Bilateral	CS0	Low
CI2	M	6;5	39	LI	2;6-3;6 y.	Bilateral	CS0	Low
CI3	F	5;10	15	EI	4;7-7 y.	Bilateral	CS0	Low
CI4	F	6;7	7	EI	4;7-7 y.	Bilateral	CS0	High
CI5	F	6;6	31	LI	3;7-4;6 y.	Bilateral	CS+	Low
CI6	F	4;7	7	EI	3;7-4;6 y.	Unilateral	CS+	High
CI7	F	7;3	13	EI	4;7-7 y.	Bilateral	CS-	Low
CI8	M	4;7	13	EI	2;6-3;6 y.	Bilateral	CS-	Low
CI9	M	4;9	13	EI	3;7-4;6 y.	Bilateral	CS+	High
CI10	M	4;6	12	EI	2;6-3;6 y.	Bilateral	CS-	High
CI11	F	4;6	18	LI	2;6-3;6 y.	Bilateral	CS-	Low
C12	F	6;9	20	LI	4;7-7 y.	Bilateral	CS+	High
C13	M	6;0	23	LI	3;7-4;6 y.	Bilateral	CS0	Low
CI14	F	3;9	12	EI	2;6-3;6 y.	Bilateral	CS0	Low
CI15	F	5;0	32	LI	2;6-3;6 y.	Bilateral	CS+	Low
CI16	F	3;8	11	EI	2;6-3;6 y.	Bilateral	CS-	Low
CI17	M	4;11	17	EI	2;6-3;6 y.	Bilateral	CS0	High
CI18	F	6;7	13	EI	4;7-7 y.	Bilateral	CS+	Low
CI19	F	5;0	21	LI	2;6-3;6 y.	Bilateral	CS+	Low

Table 6.1: Characteristics of the children with CIs.

To study the effects of maturation within our groups, we created age groups based on the auditory age of the CI participants and the chronological age of the TH children. Three groups were formed: 2;6-3;6 years (TH: N = 10; CI: N = 9), 3;7-4;6 years (TH: N = 10; CI: N = 5), 4;7-7 years (TH: N = 28; CI: N = 5).

The socio-economic status (SES) level of the children was also studied based on the education levels of both parents, by averaging the number of years they had spent in education, following the method of Le Normand (2022) according to Desrosières' classification (Desrosières et al., 1983). Two categories were determined: the high level, which includes education levels between high school and postgraduate degree (CI: N = 13; TH: N = 35), and the low level, which includes education from elementary school to a high school degree (CI: n = 6; TH: n = 12). The list of CI participants and their characteristics is presented in Table 6.1.

2.2. Tasks

2.2.1. Naming task

The children first completed a picture-naming task. The target words (n = 48) for this task were selected by the authors to include all French phonemes in initial, medial, and final syllable positions. The target words were also chosen for their early age of acquisition (referring to Chalard et al., 2003) to facilitate retrieval by the children (Philippart De Foy et al., 2018).

The target word pictures were presented to the child one at a time via a booklet, and the child was asked to orally name each picture. If the child did not respond or if the produced word did not match the target (e.g., semantic paraphasia or a random response), different prompts were provided. First, semantic cues related to the target word were given (e.g., "you can use it when it rains" for /paʁaplɥi/ - *umbrella*). If the target word was still not produced, a phonological cue was offered by providing the initial phoneme (e.g., "it starts with /s/" for /suri/ - *mouse*). If these two cues were insufficient for the child to retrieve the target word, the experimenter would say the word and ask the child to repeat it.

2.2.2. Comprehension task

The comprehension consisted in a sentence/word-picture matching task. A word or a short sentence was presented auditorily to the children, and they were asked to point to the corresponding picture in a pair of images. The task included a total of 28 items. The differences between the target words/sentences and their distractors involved : 13 number markings (e.g., "il va" - /il va/ (*he goes*) vs. "ils vont" - /il vɔ̃/ (*they go*)], 7 gender markings (e.g., "boulanger" - /bulɑ̃ʒe/ (*baker – male*) vs. "boulangère" - /bulɑ̃ʒɛʁ/ (*baker – female*)] and 8 lexical minimal pairs [e.g., "bain" - /bɛ̃/ (*bath*) vs. "banc" - /bɑ̃/ (*bench*)]. These different grammatical and lexical distinctions were based on various phonological contrasts: oral/nasal (n= 10), oral/oral (n= 3), or nasal/nasal (n= 3) vowel substitutions, as well as phonemic additions (n= 12). The list of items and an illustration of the testing interface are available in Appendix 4.

The children were presented with two images (the target image and the distractor) on a tablet. They listened to the target word or sentence through an audio recording played via loudspeakers (Bose Soundlike). The sound level was controlled to reach an average level of 60 dB. The children were then asked to point to the corresponding target image among the two images. Five practice items were provided before the task to ensure the children understood the instructions and to adjust the sound volume for optimal listening of the stimuli.

2.2.3. Narrative production tasks

Two narrative production tasks were proposed to the children: an induced narrative task and a free narrative task.

The first narrative task was the induced narrative. In the initial phase, a story with images was presented to the children. An animated story was shown on a tablet, with the animations illustrating the story to provide visual support, while a filmed narrator told the story. In order to prevent the child from focusing solely on the narrator or the animations, thereby missing information, the phases of narration by the speaker and the animation phases alternated without overlapping, allowing the child to shift from one to the other. Afterward, the child was asked to retell the story using the animations previously shown as visual support. The purpose of the induction phase was to present a story containing various twists and turns that would introduce past, future, and conditional tenses/modes, as well as gender and number markers. The goal was to encourage varied productions of grammatical markers and verb tenses from the children. The full elicited narrative, along with an illustration of the presentation interface, is available in Appendix 5.

The free narrative task involved presenting the wordless picture book “Frog, Where Are You?” (Mayer, 1969). The child was shown the book and asked to tell the story.

2.3. Procedure

The children completed the four tasks in a quiet environment, in the presence of the experimenter and, in some cases, their speech therapist. The tasks were administered in the following order: first, the picture-naming task, followed by the induced narrative production task, the comprehension task, and finally, the free narrative production task. The total testing time ranged between 35 and 60 minutes. Breaks were proposed to the children between tasks. All of the children’s productions were recorded using an H5 Zoom portable audio recorder.

2.4. Measures

2.4.1. Phonological score

The children's productions in the naming task were annotated by an initial examiner and subsequently verified by the first author using the Phon 3.1 software (Hedlung & Rose, 2020). The software, by comparing the target phonological form with the actual production as annotated, was able to extract various phonological accuracy scores. In this study, we will focus solely on a global score of percentage of correct phonemes (PCP). A more comprehensive description of the children's phonological as well as acoustic analyses of the productions are available in a previous study (Fagniart et al., 2024a).

2.4.2. Sentence/word-picture matching task scores

For the comprehension task, *d*' scores were calculated for all scores related to a specific category. First, scores were computed for each type of grammatical markers involved in the comprehension task (gender and number), as well as for all the items including minimal pairs. Second, specific *d'* scores were calculated for each of the phonological contrasts conveying the distinction between the target and the distractor: contrasts between nasal and oral vowels, oral and oral vowels, nasal and nasal vowels, or the phonological process of phonemic addition. *d'* scores were obtained by subtracting the normalized, centered, and standardized values of hit (correct detection) and false alarm (incorrect detection) rates, according to the signal detection theory (MacMillan & Creelman, 1991). Extreme scores of 0 and 1 were converted to 0.01 and 0.99, respectively, to allow for Z-score conversion.

2.4.3. Grammatical production scores and error types

The children's productions from the audio recordings of the narratives were transcribed using PHON (Hedlung & Rose, 2020) and then exported to the Computerized Language Analysis (CLAN) software (MacWhinney, 2000) for the purpose of conducting a morphosyntactic annotation of the words in the narratives using the MOR and POST functions (Parisse & Le Normand, 2000). The KidEval program was used to extract various cues of morphosyntactic development, while also classifying the different function words produced and the verb tenses used.

For the study, we focused on the following cues for analysis, known to be indicators of morphosyntactic development or linked to morphosyntactic complexity:

- Mean Length of Utterance (MLU) in morphemes (MLUm)
- The verb/utterance ratio: determining the number of utterances containing a main verb
- The number of the following function and content words: prepositions, pronouns, demonstrative pronouns, reflexive pronouns, object pronouns, subject pronouns, adjectives, adverbs, articles, possessive determiners, conjunctions, number of regular verbs, copula verbs, modal verbs, auxiliary verbs, and possessive verbs. The raw counts of these different grammatical words were divided by the total number of words produced by the child, in order to obtain a relative measure that is not influenced by sample size.
- Verb forms related to variations in tenses and moods: present, past simple (judged as equivalent to the "imparfait" in French), past perfect (judged as equivalent to the "participe passé" in French), conditional, and future. The raw counts of these different verb forms were divided by the total number of verbs produced by the child.

The annotated narratives were also reviewed by the first author to identify different types of errors, which will be analyzed. The errors observed included:

- Noun agreement errors in number ("*les cheval*" - /leʃəval/ - i.e. "*the (plural) horse (singular)*" instead of "*les chevaux*" - /leʃəvo/ - i.e. "*the (plural) horses (plural)*") and gender ("*la boulanger*" - /labulɑ̃ʒe/ - i.e. "*the baker (male)*" instead of "*la boulangère*" - /labulɑ̃ʒɛʁ/ - i.e. "*the baker (female)*")
- Verb agreement errors in number ("*les amis vient*" - /lezamivjɛ̃/ - i.e. "*the friends is coming*" instead of "*les amis viennent*" - /lezamivjɛn/ - i.e. "*the friends are coming*").
- Verb form errors: auxiliary ("*il a parti*" - /ilapaʁti/ instead of "*il est parti*" - /ilɛpaʁt/), form ("*ils se marier*" - /ilsəmaʁje/ instead of "*ils se mariaient*" - /ilsəmaʁjɛ/), overgeneralization ("*il parta*" - /ilpaʁta/ instead of "*il partit*" - /ilpaʁti/)
- Substitution of function words: preposition ("*il tombe sur la fenêtre*" - /iltɔ̃bsyʁlafənɛtʁ/ instead of "*il tombe par la fenêtre*" - /iltɔ̃bpaʁlafənɛtʁ/), contracted article ("*de le cheval*" - /dələʃəval/, instead of *"du cheval"* - /dyʃəval/), clitic pronoun (*"il le regarde (mention to a female character)"* - /illəʁəgaʁd/, instead of *"il la regarde"* - /illaʁəgaʁd/), others

- Deletion of function words: determiners in general and before monosyllabic (*"chien"* - /ʃəval/, instead of "*le chien"* - /ləʃjɛ̃/) vs bisyllabic nouns (*"cheval"* - /ʃəval/, instead of *"le cheval*" - /ləʃəval/), prepositions ("il *tombe la fenêtre*" - /il tɔ̃b la fənɛtʁ/ instead of "*il tombe par la fenêtre*" - /iltɔ̃bpaʁlafənɛtʁ/)
- Addition of function words: pronominal redundancy ("*le garçon il va*" - /ləgaʁsɔ̃ilva/, instead of "*le garçon va*" - /ləgaʁsɔ̃ilva/), various additions

In order to also obtain an indicator related to the level of lexical development, the lexical diversity index D, derived from the VOCD procedure in KidEval (Duran et al., 2004), was computed. This index was created to avoid being influenced by sample size, unlike the Type/Token Ratio (TTR) index, which increases with the size of the corpus. The index is calculated based on a mathematical model of the probability that a new word will be introduced as the corpus lengthens. This mathematical model is compared to the actual produced corpus to obtain the D index. This index has proven to be more reliable for evaluating corpora of different sizes and has demonstrated its ability to discriminate between different types of speakers (Duran et al., 2004).

2.5. Statistical analysis

Linear generalized mixed models, employing the lme4 package (version 1.1-34; Bates et al., 2015) within the R software (R Core Team, 2022), were used to compare groups among the various measures on the children's speech productions. The models were constructed using the different independent variables of interest, namely:

- Auditory status: cochlear implant children (CI) ; typical hearing children (TH)
- CS exposure : CS0 = no CS exposure ; CS- = occasional CS exposure ; CS+ = early and frequent CS exposure ; TH
- Auditory age group: 2;6-3;6 / 3;7-4;6 / 4;7-7
- Implantation age group : CI/EI = early (< 18m.) ; CI/LI = late (> 18 m.) ; TH
- Socio-economic status (SES) : low-SES ; high-SES

The interaction between auditory status*auditory age group and auditory status*SES were also tested. A random intercept effect for each subject was included in the models. The significance of fixed effects was evaluated using Chi-squared tests and corresponding p-values, performed through the ANOVA function in the Car package (Fox & Weisberg, 2018) applied to the model. Additionally, post-hoc analyses were carried out using the emmeans package (Lenth et al., 2023). Pearson correlation coefficients were calculated between the different measures.

3. Results

3.1. Phonological accuracy

The percentages of correct phonemes produced in the naming task were analyzed to document phonological accuracy. Children in the CI group had significantly lower percentages of correct total phonemes (CI: 76.7 - TH: 90.6; $\chi^2(1)$= 25.78; p<.001). CS exposure displayed a significant effect ($\chi^2(3)$= 28.75; p<.001), with the CS0 and CS+ showing significantly lower score compared to TH group (CS0 = 72.5 ; CS- = 82.2 ; CS+ = 76.8 ; TH = 90.6). An effect of auditory age group ($\chi^2(2)$= 10.36; p=.005) as well as an interaction effect between auditory age group and auditory status ($\chi^2(2)$= 10.2; p=.006) was observed. Specifically, the performance of children in the TH group increased with advancing age group, while in the CI group, the 3;7-4;6 age range showed lower scores compared to the other groups. No effect of implantation age or SES level was observed.

3.2. Sentence/word-picture marching task

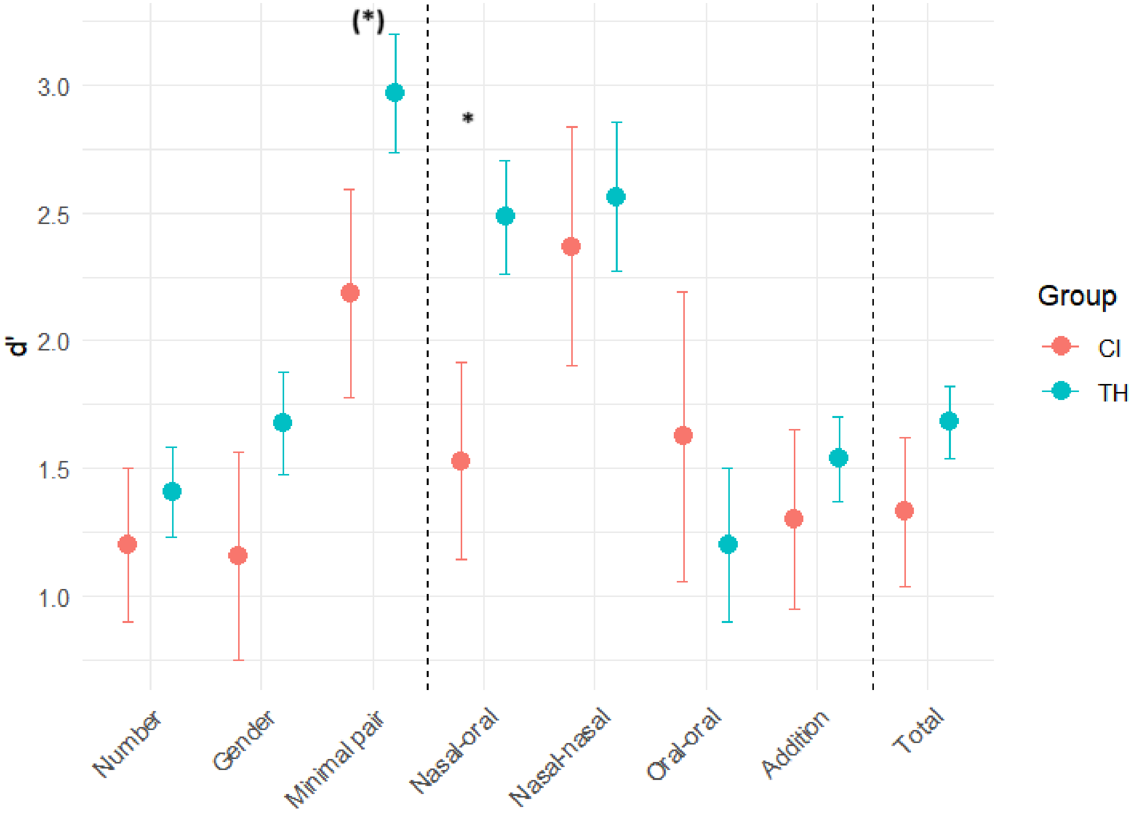

Figure 6.1: Means and error bars corresponding to ± one standard deviation of scores partitioned according to the types of grammatical markers and types of phonological oppositions, as well as the total scores on the sentence/word picture matching task for the CI and TH groups. Significant differences between groups are indicated with * (p<.05), ** (p<.005) or * (p<.001). p-values at the margin of significance (between .1 and .05) are represented by (*).**

A marginal group effect favoring the TH group was observed for minimal pairs (2.97 vs 2.13; β = 0.78, SE = 0.44, t(64) = 1.74; p = .08). No effect of auditory status was observed for number and gender markers. Considering the phonological mechanisms involved in grammatical oppositions, a significant effect of auditory status, favoring the TH group, was observed only for oppositions based on distinctions between nasal and oral vowels (2.48 vs 1.53; β = 0.95, SE = 0.42, t(64) = 2.25; p = .02). No significant effects were found for distinctions between nasal and nasal vowels, oral and oral vowels, or phonemic additions (see Figure 6.1).

A marginal effect of CS exposure was observed only on items where the distinction was marked by nasal/oral vowels ($\chi^2(3)$ = 7.1; p = .06), with the CS-group showing the lowest values. An effect of implantation age group was also observed on these items ($\chi^2(3)$ = 6.1; p = .04), with the group implanted after 16 months showing lower values than the TH group. An interaction effect between chronological/auditory age group was observed on scores for minimal pairs ($\chi^2(2) = 6.99$; p = .02) and on items with nasal/oral vowel distinctions ($\chi^2(2) = 7.05$; p = .03), with children in the TH group showing increased scores with advancing age, while in the CI group, children in the intermediate age group (3;7-4;6 years) had the lowest scores. No effect of socio-economic level groupings was found.

3.3. Results of narrative productions

3.3.1. Developmental cues

Table 6.2 presents the mean values of MLUm, the verb/utterance ratio, as well as the lexical index D values by type of narrative and by group (CI and TH).

Measure	Narrative type	CI (mean)	TH (mean)	p-values
MLU Morphemes (MLUm)	Elicited	4.54	5.59	.01
	Free	5.03	5.92	.04
	p-values	.03	.03	
Verbs/Utterances	Elicited	0.72	0.82	NS
	Free	0.67	0.86	.01
	p-values	NS	NS	
D	Elicited	26.8	39.4	<.001
	Free	23.7	31.4	.005
	p-values	NS	<.001	

Table 6.2: Means and p-values of the test associated with MLUm values, verb/utterances ratio, and D index according to the type of narrative and group (CI - TH). NS = non-significant values.

A significant effect of auditory status was observed on MLUm values, favoring the TH group (β = 0.89; SE = 0.42; t(64) = 2.08; p = .04). This effect was present for both the elicited narrative (β = -1.05, SE = 0.42; t(64) = -2.46; p = .01) and the free narrative (β = -0.89, SE = 0.42; t(64) = -2.09; p = .04). An effect of narrative type was observed in both groups (β = -0.49; SE = 0.27; t(64) = -2.1; p = .03), with higher MLUm values in the free narrative. Similarly, children in the TH group generally achieved a better verb/utterance ratio (β = 0.19; SE = 0.07; t(64) = 2.56; p = .01). This effect was only present for the free narrative (β = -0.19; SE = 0.07; t(64) = -2.56; p = .01). A marginal interaction effect was observed between narrative type and auditory status ($\chi^2(1) = 3.22$; p = .07), with children in the CI group having a better verb/utterance ratio in the elicited narrative, whereas this ratio was equivalent between the two tasks in the TH group. The lexical diversity index *D* also showed a significant overall group effect in favor of the TH group (β = 8.13; SE = 2.66; t(64) = 3.05; p = .003), with children in the TH group exhibiting higher values for the induced narrative (β = -12.6; SE = 2.67; t(64) = -4.7; p < .001) and the free narrative (β = -8.13; SE = 2.67; t(64) = -3.05; p = .003). An effect of the type of narrative was observed on the *D* values ($\chi^2(1)$ = 30.02; p < .001), as well as a marginal auditory status*task interaction ($\chi^2(1)$ = 3.02; p = .08), with the induced narrative causing higher *D* to a greater extent among children in the TH group.

An effect of CS exposure was observed on the lexical diversity index ($\chi^2(3)$ = 20.12; p < .001), with significantly lower scores in the CS0 and CS+ groups compared to the TH group (CS0: 25.3 vs. CS-: 28.0 vs. CS+: 23.2 vs. TH: 35.6), as well as a CS*task interaction ($\chi^2(3)$ = 7.8; p = .04), with the observed differences appearing only in the elicited narrative. An effect of the auditory age group was also observed on the *D* index ($\chi^2(2)$ = 13.36; p = .001), with children who had late implantation having significantly lower scores than children in the TH group. No effect of socio-economic level groupings was found.

A significant auditory age group effect ($\chi^2(2)$ = 33.46; p<.001) as well as a marginal interaction effect between auditory age group and auditory status ($\chi^2(2)$ = 4.78; p = .09) was observed for the MLUm scores, as well as for the verb/utterance ratio ($\chi^2(2)$ = 28.05; p < .001) and for the lexical diversity index ($\chi^2(2)$ = 8.75; p = .01), with both groups showing increased scores with advancing age groups.

3.3.2. Function words

Table 6.3 displays the mean percentages of function and content words produced in the CI and TH groups., as well as the p-values of the tests evaluating the effects of auditory status, CS exposure, and age groupings.

Word type	CI mean	TH mean	Auditory status effect	Auditory age group effect	Auditory age group effect*auditory status group effect	CS exposure effect	Implantation age group effect
Preposition	6.5	9.1	<.001	.02	.04	.002	
Pronoun total	0.4	0.6					
Demonstrative pro.	1.8	1.3		<.001		.03	
Reflexive pronoun	0.6	1.3	<.001	.05		<.001	.002
Object pronoun	0.2	0.4	.01				
Subject pronoun	11.9	12		.08			
Adjective	2.1	2.3					
Adverb	3.4	3.9		.08			
Article determiner	12.6	13.8	.04	.05	.06		
Possessive det.	1	1.8	.002			.002	
Conjunction	5.6	4.3	.01			.002	.02
Regular verb	6.5	8.5	.001	<.001		.009	
Copula verb	0.64	0.45		<.001			
Modal verb	2.4	2.8					
Auxiliar verb	6.1	4.6	.01			.006	.004

Table 6.3: Means of the percentages of occurrence of different function and content words according to the CI and TH groups, and p-values associated with the different group comparisons.

Effects of auditory status in favor of the TH group were observed for the percentages of prepositions, reflexive and object pronouns, article and possessive determiners, as well as regular and auxiliary verbs. A significant effect of CS exposure is observed on the average percentages of prepositions ($\chi^2(3) = 14.46$; $p = .002$), with the highest values found in the CS+ group, followed by CS- and CS0. An effect is also observed for the percentages of reflexive pronouns ($\chi^2(3) = 13.36$; $p = .003$), possessive determiners ($\chi^2(3) = 14.78$; $p=.002$), conjunctions ($\chi^2(3) = 13.94$; $p=.003$) and regular verb ($\chi^2(3) = 11.36$; $p=.009$), with significantly lower values for the CS- group. However, the CS- group shows higher percentages of demonstrative pronouns ($\chi^2(3) = 6.56$; $p = .03$) and auxiliar verbs ($\chi^2(3) = 12.25$; $p = .006$). Regarding the implantation age groups, fewer percentages of reflexive pronouns ($\chi^2(2) = 12.11$; $p = .002$), conjunctions ($\chi^2(2) = 7.38$; $p = .02$) and auxiliar verbs ($\chi^2(2) = 10.78$; $p = .004$) are observed in children who were implanted after 18 months. No effect of socio-economic level groupings was found.

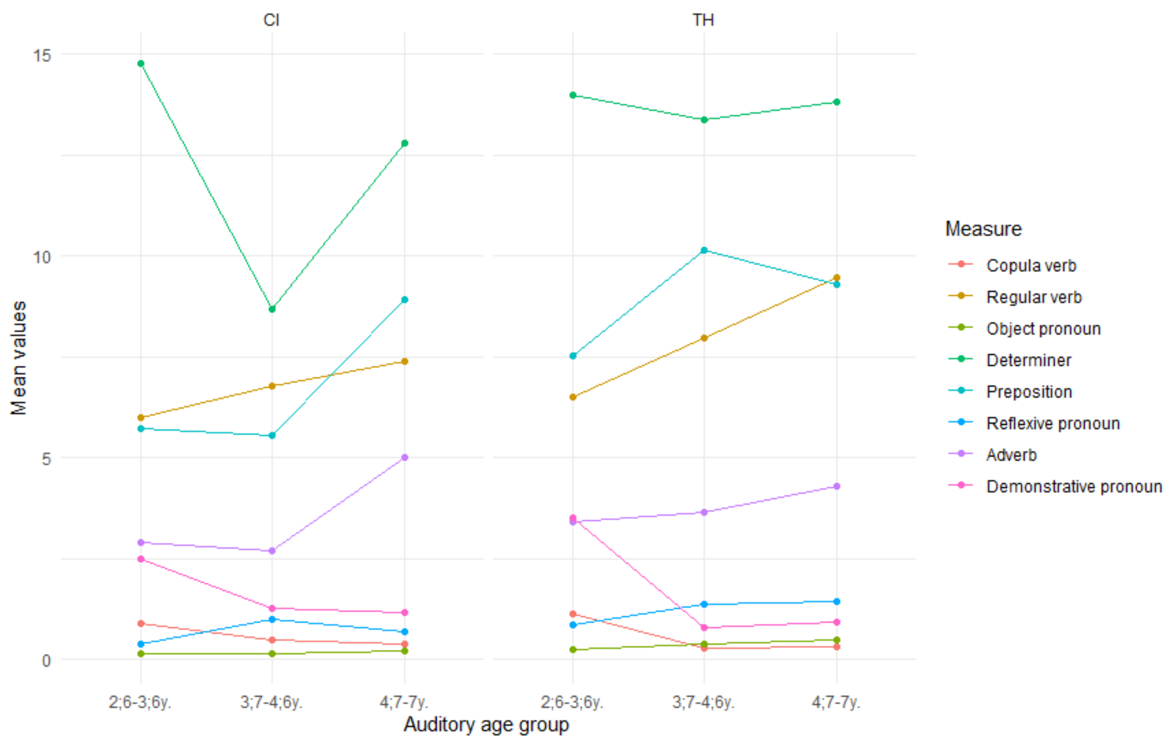

Figure 6.2: Mean percentages of occurrence by function words according to auditory age groups and CI and TH groups.

Chronological/auditory age group effects are observed for all function words percentages except for adjectives, object pronouns, possessive determiners, modal verbs, and auxiliary verbs, whose values remain stable across groups. Figure 6.2 illustrates the averaged percentages of the different function words based on age group and auditory status: a general trend of increasing average values for most function words can be seen in both groups, except for determiners in the CI group, which show a decrease in the 3;7-4;6 age group, and for prepositions, where percentages increase in the 4;7-7y group for the CI group but remain stable after 3;7y for the TH group. In both groups, the percentage of demonstrative pronouns and copula verbs decreases with age.

3.3.3. Verbal morphology

Table 6.4 provided the averaged percentages of verbal forms produced by children in the CI and TH groups, as well as the p-values of the tests examining the effect of auditory status, CS exposure, and age groups.

	CI	TH	Auditory status effect	Auditory age group effect	Auditory age group effect*group effect	CS exposure effect	Implantation group effect
Present	54.6	47.6	.06	<.001			.01
Conditional	0.6	1.7	.04				
Future	0	0.6	.04				
Past simple	3.9	10.2	.01	<.001		.09	.03
Past perfect	17.7	11.5	.001			.004	
Infinitive	9.1	10.8			.01		

Table 6.4: Means of the percentages of occurrence of different verbal forms according to the CI and TH groups, and p-values associated with the different group comparisons.

Significant effects in favor of the TH group were observed for the conditional, future, and past simple tenses, as well as a marginal effect on the production of the present tense. In contrast, children in the CI group produced significantly more past perfect verbs. An effect of exposure to CS is observed for the use of the past perfect ($\chi^2(3) = 12.94$; $p = .004$), with higher values for the CS+ group, and marginally for the past simple tense ($\chi^2(3) = 6.3$; $p = .09$), with lower values for the CS- group. An effect of the age at implantation is observed for the use of the present ($\chi^2(2) = 8.3$; $p = .01$) and the past simple tense ($\chi^2(2) = 6.93$; $p = .03$), with lower average values among children whose implantation occurred after 18 months. No effect of socio-economic level groupings was found.

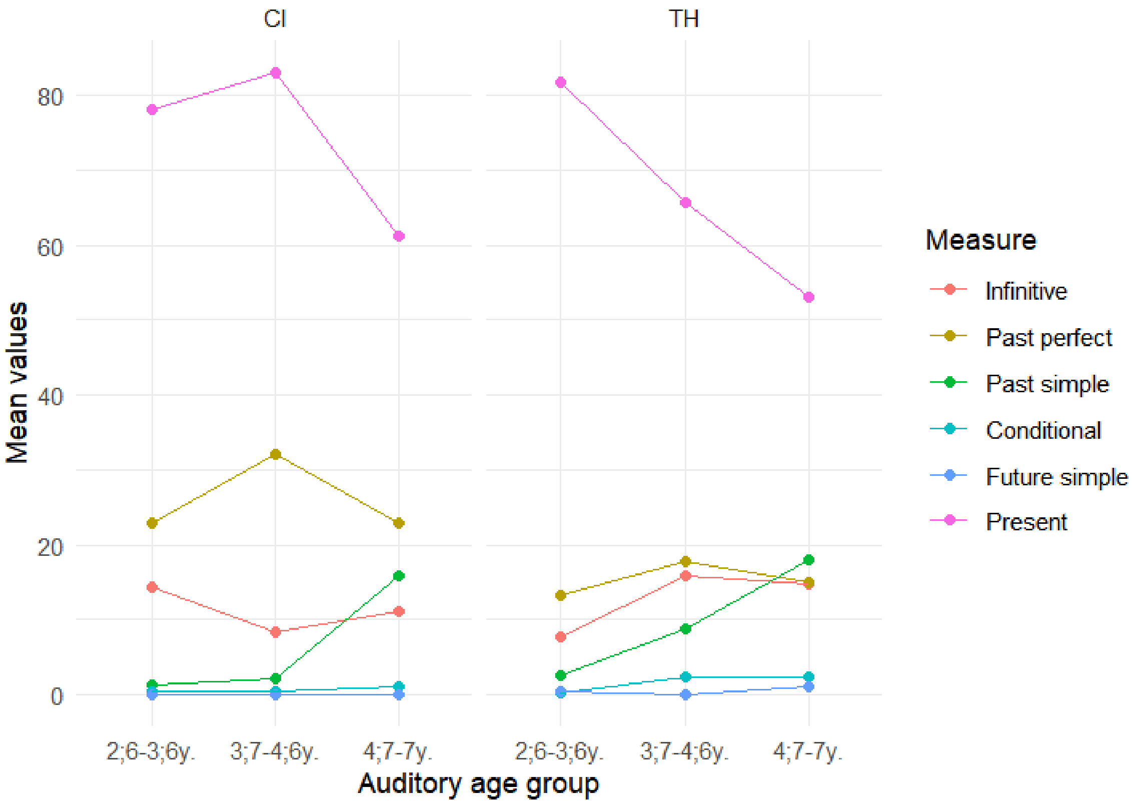

Figure 6.3: Mean percentages of occurrence of verbal forms according to auditory age groups and CI and TH groups.

Figure 6.3 illustrates age effects: both groups showed an increase in values with advancing age groups for the past simple tense and a decrease for the present tense. An interaction was found for infinitives ($\chi^2(2) = 7.98$; $p = .01$), with percentages decreasing in the CI group while increasing in the TH age groups.

3.3.4. Errors

Table 6.5 displays the mean of percentages of the different types of errors among the CI and TH groups, as well as the p-values of the tests associated with the different variables of interest.

		CI	TH	Auditory status effect	Auditory age group effect	Auditory age group effect* auditory status group effect	CS exposure effect	Implantation age group effect
Nominal agreement	Number	0.03	0.02				.08	
	Gender	0.36	0.16	.05				
	i.e. det+noun	.042	0.14	.001			<.001	
Verbal agreement	Number	0.12	0.05	.04			.01	
Verbal tense	Auxiliary	0.07	0.03			.03		
	Overgeneralization	0.01	0.09					
	Form	0.2	0.09	.05				.02
Omission	Determiners	3.47	0.39	<.001		.01	<.001	.002
	bef. 1 syll. noun	0.65	0.08	<.001	.05	.002	<.001	<.001
	bef. 2 syll. noun	2.1	0.3	.001		.005	<.001	.004
Addition	Pronominal redundancy	1.6	0.77	.007			.009	
	Other	0.12	0.04	.03			.05	.07

Table 6.5: Means of the percentages of occurrence of different error types according to the CI and TH groups, and p-values associated with the different group comparisons.

An effect of auditory status was observed in verbal agreement in number ($\chi^2(2) = 3.89$; $p = .04$) and nominal agreement in gender ($\chi^2(3) = 8.54$; $p = .01$), including determiner-noun agreement in gender ($\chi^2(2) = 10.7$; $p = .001$), verbal tense form errors ($\chi^2(3) = 3.71$; $p = .05$), the omission of determiners ($\chi^2(2) = 11.69$; $p = <.001$) and prepositions ($\chi^2(2) = 11.67$; $p = <.001$), as well as the addition of various elements ($\chi^2(2) = 4.59$; $p = .03$) and pronominal redundancies ($\chi^2(3) = 7.16$; $p = .007$). Children in the CI group made more of these types of errors than children in the TH group. Regarding determiners, it is noteworthy that children in the CI group significantly omit determiners more often before two-syllable words than one-syllable words ($t(64) = -3.58$; $p < .001$), whereas the children of the TH group do not show a syllabic context effect on the number of omissions.

An effect of exposure to CS is observed on the number of preposition omissions ($\chi^2(3) = 13.46$; $p = .003$), with more errors of this type in the CS+ group, as well as for verbal agreement in number (chi2(3) = 9.9; p =.01) and the agreement between determiner and noun in gender ($\chi^2(3) = 17.84$; $p < .001$), with more errors in the CS- group. An effect of CS is also observed on the number of added function words ($\chi^2(3) = 7.5$; $p = .05$) and pronominal redundancy ($\chi^2(3) = 7.16$; $p = .007$), with fewer errors of this type in the CS- group. More error of determiner omissions were found in the CS0 group (chi2(3)= 19.7; p<.001). Regarding implantation age, an effect is observed on the number of verb form errors ($\chi^2(2) = 7.59$; $p = .02$), the number of determiner omission ($\chi^2(2) = 11.86$; $p = .002$), and marginally on the number of added function words ($\chi^2(2) = 5.26$; $p = .07$) with fewer errors in the group who received their CI < 18m. An interaction effect between SES and auditory status is observed for the number of determiner omissions in front of bisyllabic words ($\chi^2(1) = 3.68$; $p = .05$), with fewer occurrences of this type of error in children with low SES.

Interaction effects between chronological/auditory age groups and hearing status were observed in the number of auxiliary substitutions ($\chi^2(2) = 7$; $p = .03$), with a decrease in the CI group as age increased, while remaining very low across age groups in the TH group. The same interaction was observed for the number of determiner omissions ($\chi^2(2) = 8.28$; $p = .01$), with a significant decrease in this type of error in the oldest age group within the TH group, while being more frequent in the 3;7-4;6 age group in the CI group, both for determiners before monosyllabic ($\chi^2(2) = 11.97$; $p = .002$) and bisyllabic words ($\chi^2(2) = 10.3$; $p = .005$).

3.4. Links Between Receptive and Productive Tasks and Phonological Scores

Figure 6.4 represented the different correlation scores for the CI and TH groups between the phonological development score (PCP), on one hand, and the averaged lexical diversity index of the two narratives (*D*) on the other hand, with the different sub-scores of the sentence/word-picture matching tasks.

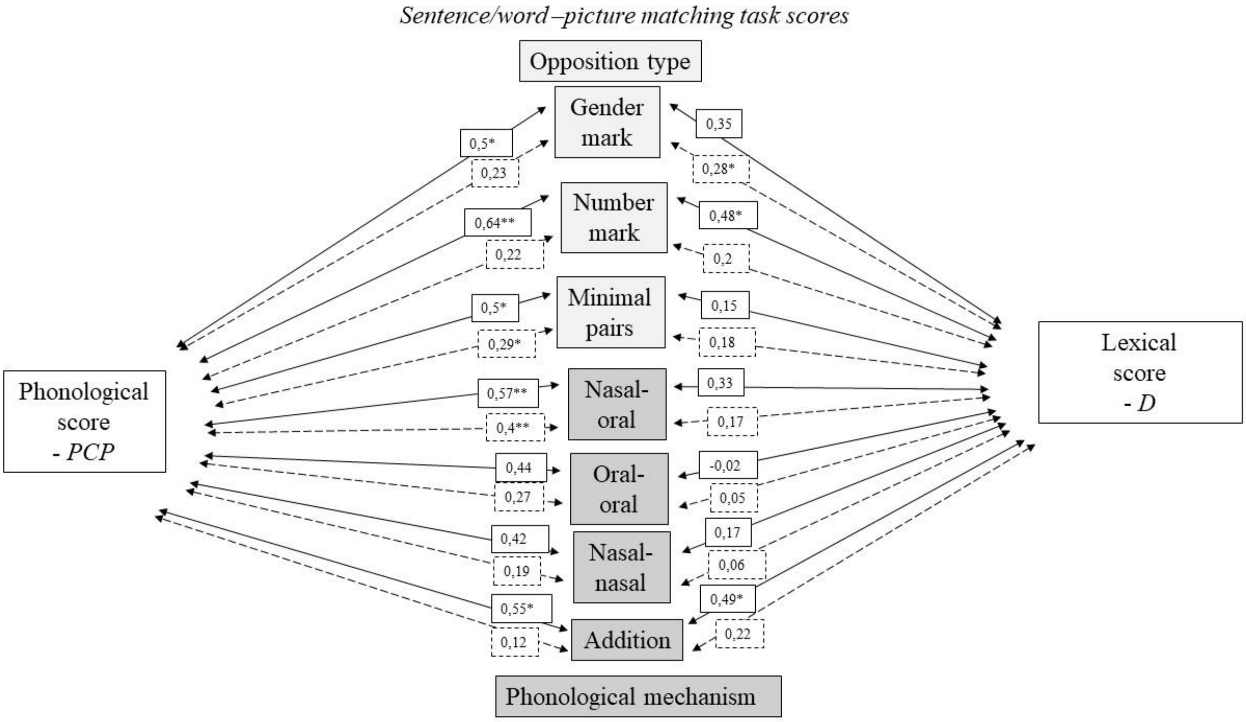

Figure 6.4: Pearson coefficients and associated significance levels between phonological scores, lexical diversity scores, and the various scores on the pointing task. Solid arrows refer to the CI group, while dashed arrows refer to the TH group. Significant correlations are indicated with * (p<.05), ** (p<.005) or * (p<.001).**

Regarding the type of opposition, the phonological score was significantly and strongly correlated with the scores of number markers and the scores on minimal pairs, and moderately correlated with the scores of gender markers among children in the CI group. *D* scores were moderately correlated with number marks score. Among children in the TH group, a moderate and significant link was observed between the PCP score and the score on minimal pairs, as well as between the *D* scores and gender markers. Concerning scores according to the type of phonological mechanism, strong and significant links were observed between the phonological scores and the sub-scores related to the nasal-oral distinction and phonemic additions in the CI group. The sub-score related to phonemic additions was also moderately correlated with the phonological and *D* scores. A moderate and significant link was observed between the phonological score and the sentence/word-picture matching task scores related to the distinction between nasal and oral vowels in the TH group.

Figure 6.5 represents the different correlation coefficients for the CI and TH groups between the phonological development score (PCP) on one hand, and the averaged lexical diversity index of the two narratives (*D*) on the other hand, with the morphosyntactic development indices MLUm and the verb/utterances ratio, as well as with the number of verbs in the imperfect tense, reflexive pronouns, grammatical errors, and pronominal redundancies. This choice of verbal tense, function word, and error was made by selecting those that showed significant differences in terms of auditory status in the previous analyses of this study (section 3.3).

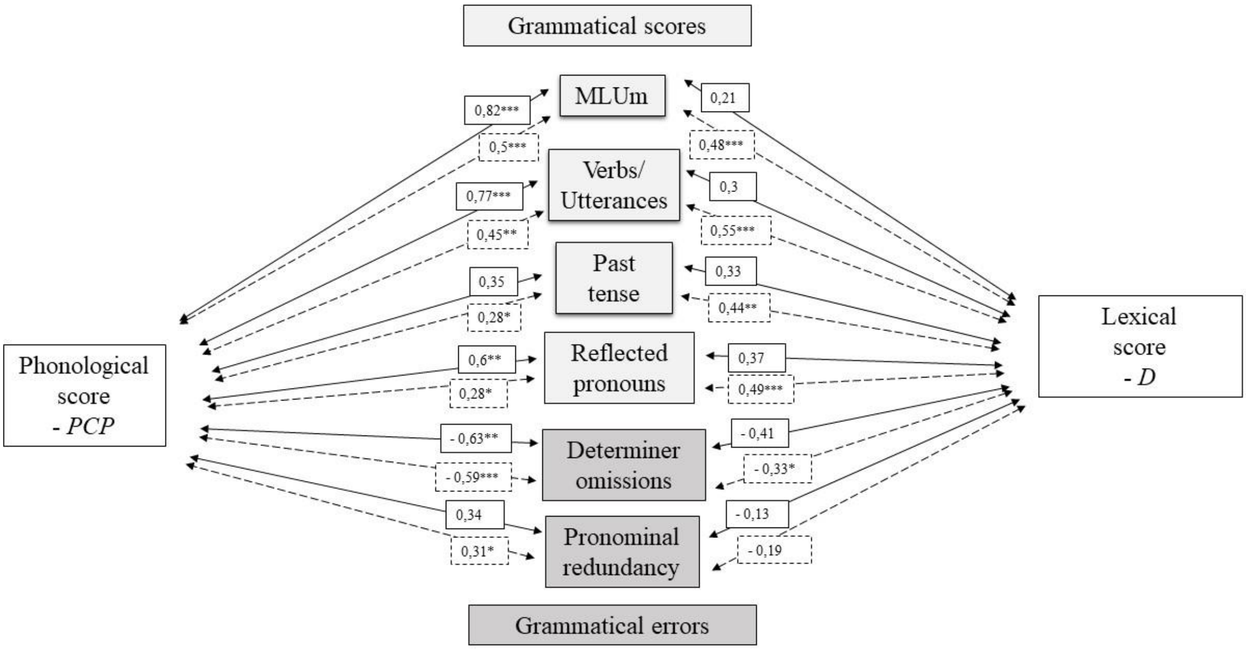

Figure 6.5: Pearson coefficients and associated significance levels between phonological scores, lexical diversity scores, and the grammatical scores and error types. Solid arrows refer to the CI group, while dashed arrows refer to the TH group. Significant correlations are indicated with * (p<.05), ** (p<.005) or * (p<.001).**

The MLUm and verb/utterances indices both exhibited strong and significant correlations with the phonological score among children in the CI group, and moderately with the TH group. These same cues showed moderate to strong correlations with the *D* score, but only within the TH group. In the TH group, weak to moderate correlations were observed between the number of verbs in the imperfect tense and the number of reflexive pronouns with the PCP and *D* scores, correlations that were not observed in the CI group. The phonological scores were strongly negatively correlated with the presence of determiner deletions in both groups, and moderately negatively with the *D* score in the TH group. The presence of pronominal redundancies was positively and moderately correlated with the phonological score in the TH group.

Figure 6.6 presented the different sub-scores of the sentence/word-picture matching task with the morphosyntactic development index MLUm.

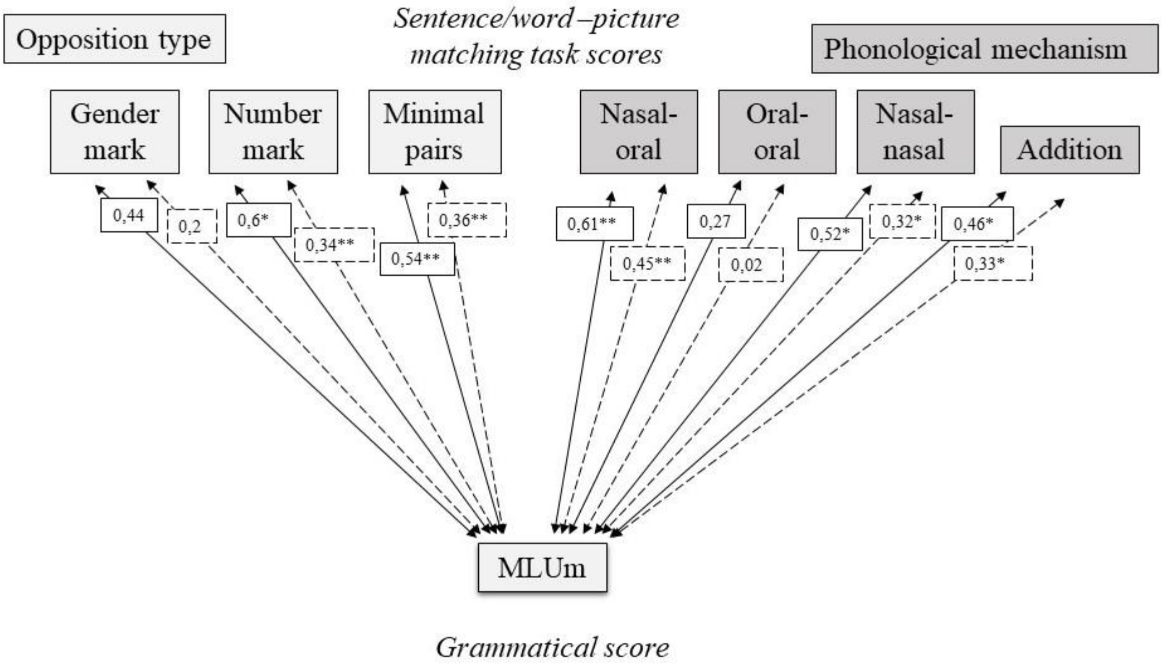

Figure 6.6: Pearson coefficients and associated significance levels between sentence/word-picture matching task scores and MLUm values. Solid arrows refer to the CI group, while dashed arrows refer to the TH group. Significant correlations are indicated with * (p<.05), ** (p<.005) or * (p<.001).**

Moderate to strong significant links were observed between number markers and minimal pairs with MLUm in both groups. Regarding phonological mechanisms, a strong and significant link was observed between the MLUm score and the sub-score related to distinctions between nasal and oral vowels in children in the CI group, with this link being moderate in the TH group. A moderate link was also observed between MLUm and the sub-score related to distinctions between nasal vowels and to phonemic additions in both groups. Note that similar relationships are generally observed between these different scores and the verb/utterance ratios, with the exception of the presence of additional strong (CI) and moderate (TH) correlations with gender marking (CI: 0.64; p = .003 - TH: 0.38; p = .008) and with the score implying distinction between two nasal vowels (CI: 0.38 ; p = .1 - TH: 0.36; p = .2). It is also interesting to note a moderate negative correlation between the omission of determiners before monosyllabic words and the sub-score related to distinctions between nasal and oral vowels in both groups (CI: -0.46; p = .04 - TH: -0.31; p = .03), while this same sub-score shows a significant negative correlation with the omission of determiners before monosyllabic words only in the TH group (CI: -0.33; p = .2 - TH: -0.37; p = .009).

4. Discussion

The present study aimed to investigate, within a group of children with cochlear implants (CI) and their typically hearing (TH) peers, grammatical production skills through narrative production, as well as morphophonological reception skills targeting grammatical marks and minimal pairs based on the distinction between French nasal and oral vowels. The study examined the relationships between these skills and phonological skills, assessed through a picture-naming task. Various individual and environmental variables such as chronological/auditory age, socio-economic status (SES) level, exposure to Cued Speech (CS), and the age of implantation were also considered.

4.1. Grammatical and lexical morphemes processing

In the morpheme identification task, an effect of auditory status was observed only for the minimal pairs and the score that included items where the morphemic opposition was carried by nasal vs. oral vowels. This finding supports the hypothesis of increased difficulty in processing certain phonological features, specifically vowel nasality, which has a significant impact on morphemic processing. These results are in line with difficulties in identification and discrimination of nasal and oral vowels already observed in children with CI(s) (Fagniart et al., 2024a). Given that the minimal pairs mostly consisted of oppositions between nasal and oral vowels, it is not surprising that the score associated with minimal pairs was generally lower than that of typically hearing children. In contrast, the observation that scores differed significantly between groups for the items carrying distinctions between nasal and oral vowels, but not across all scores related to gender and number marking, seem to support the perceptual hypothesis of MS difficulties encountered by children with CIs, rather than a global grammatical deficit as proposed by some authors (Benassi et al., 2021; Majorano et al., 2024).

4.2. Narrative productions skills

The analysis of narrative productions revealed significantly lower scores in developmental cues in CI children, specifically lower MLU (mean length of utterance) and D (lexical diversity index) values, as well as a lower verb/utterance ratio. Lower MLU values have already been reported in the literature (Hansson et al., 2017; Majorano et al., 2024; Nittrouer et al., 2018; Szagun, 2001), which has led to conclusions about increased vulnerability in MS skills among CI children in production. The verb/utterance ratio highlights the number of complete sentences, meaning those that include a main verb. The ratio of the CI group is significantly lower than that of the TH group (ranging from 0.72 for the induced narrative to 0.67 for the free narrative, compared to 0.82 and 0.86 in the TH group). A significant proportion of utterances are incomplete in the CI group, which has also been observed in a study of Italian-speaking children (Majorano et al., 2024), and further supports the observation of grammatical difficulties in these children. It is noteworthy that an effect of the type of narrative elicitation is observed in both groups for MLUm values, with higher values in the free narrative, whereas only the CI group shows a higher verb/utterance ratio in the induced narrative. It appears that presenting a prior model encouraged the children in this group to use verbs in their sentences, enabling them to reach the level of the TH children.

The analysis of function words revealed differences between our groups in the production of prepositions, reflexive and object pronouns, articles and possessive determiners, and regular verbs, with these occurring more frequently in the CI group. In contrast, demonstrative and subject pronouns, as well as adjectives, adverbs, and copula or modal verbs, were produced similarly in both groups. Conjunctions and auxiliary verbs, however, were observed in a greater proportion in the CI group. This differentiated effect of auditory status on the acquisition of function words had already been observed in French (Le Normand, 2004;Le Normand & Thai-Van, 2023) and was attributed to the more or less lexicalizable and/or accented status of certain function words, giving them a perceptual advantage. The study of verb tenses and mode produced by the children revealed a higher usage of the conditional, past simple and future in the TH group, while the infinitives were produced equivalently in the groups. Given the MS difficulties observed in our sample, it is not surprising to see more difficulties in using complex tenses like the past simple, future or conditional, as these tenses are associated with complex and less salient morphophonological oppositions in spoken language and are complex in terms of reference, especially in the case of the conditional. The children in the CI group seem to use the present past perfect more often. The present mark tenses are frequent and relatively stable in French, and the use of an auxiliary can be more perceptually salient in past perfect, with a past participle phonologically stable.

The analysis of errors revealed more errors in nominal agreement (within the determiner+noun relationship) in CI children, as well as more deletions of determiners and prepositions, along with more pronominal redundancies, various additions and errors of verbal tense form. Morphological errors related to gender marking have also been previously observed in children with CI in French (Le Normand & Thai-Van, 2023) as well as in other languages (Moreno-Torres & Torres, 2008; Szagun, 2004a), with difficulties in grammatical morphology manifesting as morpheme substitutions. These errors in verbal or nominal agreement, manifested through substitutions, suggest a potential grammatical deficit and/or specific processing difficulties. However, in our sample, the children also made a number of omissions of function words, particularly prepositions and determiners. Determiner omissions have been suggested as a sign of perceptual difficulties (Moreno-Torres & Torres, 2008) and/or prosodic difficulties (Le Normand & Moreno-Torres, 2014; Le Normand & Thai-Van, 2023). In line with Le Normand (Le Normand & Moreno-Torres, 2014), we evaluated whether the occurrence of determiner omissions was more or less frequent depending on whether the following word was monosyllabic or bisyllabic. The children in the CI group showed a clear effect of the syllabic context of the noun on determiner omission, with bisyllabic words being more vulnerable. This effect is a sign of the correct use of relevant suprasegmental cues in the French language, where the iambic metric structure (alternation of strong-weak syllables in binary foot) is dominant (Demuth & Tremblay, 2008). Similar to Le Normand's (2014) study, our data suggest a benefit of prosodic bootstrapping in morphosyntactic development, most likely through the use of acoustic information (segmental lengths and intensity) associated with the rhythmicity of the speech stream. This developmental profile is similar to that of typically hearing (TH) children in early grammar (Demuth & Tremblay, 2008).These findings, combined with the observation of substitution-type errors, may suggest that children with CI experience difficulties of mixed origin: perceptual difficulties lead to challenges in mastering verbal and nominal agreements, associated with developmentally delayed bootstrapping mechanisms.

An integrative explanatory approach for these various findings is provided by Moreno-Torres (Moreno-Torres & Moruno-López, 2014). In that study, the authors observed different error profiles in suprasegmental aspects compared to hearing peers, which may suggest a tendency of CI children to reproduce correct syllabic sequences of the language without accessing the complete prosodic structure (perception of prosodic variations related to F0). The authors integrate their various findings into theoretical models of speech motor control (Hickok, 2012), proposing that the segmental elements of speech rely on both auditory-motor and somatosensory-motor cues. While the former cues are the first to be employed in development due to early guidance by auditory feedback, the latter cues are used later during the initial stages of speech production (babbling, first words). The literature suggests to Moreno-Torres and colleagues that children with cochlear implants (CI) are more efficient in using auditory-motor cues, allowing them to quickly acquire a certain number of segments and the syllabic structure of their language after implantation. However, they face difficulties arising from their perceptual limitations, explaining the challenges in mastering certain phonological features. In contrast, they find it harder to rely on somatosensory-motor cues, which are more closely associated with phonemic units and implicit learning, possibly explaining the increased difficulty in perceiving consonantal and prosodic units. In this context, the authors propose a deficit in the use of the dorsal stream of the brain, based on the dual-stream processing model (Friederici, 2012; Hickok & Poeppel, 2004). According to this theory, the dorsal stream is associated with auditory-motor motor integration responsible for segmental-level processing, while the ventral stream, associated with auditory-motor conceptual integration, is used for semantic-lexical access. This hypothesis also highlights difficulties in implicit learning associated with the dorsal stream deficit, which may explain the increased dependence on explicit teaching and the significant inter-individual variability characteristic of this population. This explanatory framework is fully consistent with the observations of the present study: children with cochlear implants (CI) struggle more to acquire function words, whose conceptual representation is less prominent and less easily accessible through explicit teaching. This leads to difficulties such as substitutions and omissions of morphemes, also due to incomplete perception of the prosodic elements of the language.

It is important to note that the children in the CI group also exhibited lower performance in terms of lexical diversity. This finding might seem contradictory to the literature that suggests a preservation of lexical skills (Caselli et al., 2012; Duchesne et al., 2009; Rinaldi et al., 2013). However, a similar result was obtained in narrative productions by Le Normand & Thai-Van (2023). Methodological differences could explain this discrepancy between studies, as those reporting a selective grammatical deficit typically employed formal language assessment tests, which mainly involved tasks such as naming or picture identification to assess receptive and/or productive lexical levels. In contrast, the language mechanisms involved in narrative production are more complex and closer to an ecological language production situation. Our present data corroborate the author’s findings, suggesting that lexical development might also pose long-term challenges for children with CI. The fact that the children in our study did not benefit from prior narrative presentation during the elicited narrative task in terms of lexical diversity, unlike the TH group children who show higher D values in the elicited narrative task, seems to indicate a greater vulnerability in processing lexical items presented in their linguistic environment.

4.3. Is there a link between lexical, phonological and grammatical abilities?

The relationships between the phonological, morphosyntactic, and lexical components of language among our groups of children showed different profiles consistent with specific difficulties encountered by CI children.

Regarding the task of processing grammatical and lexical morphemes, strong links were observed between phonological skills and the gender and number marking scores only among children in the CI group. Children with better phonological skills were able to more effectively process gender and number markings within sentences. A strong link in CI children and a moderate one in TH children was also observed between the phonological score and both the minimal pairs and the sub-score associated with items distinguished by nasal and oral vowels. This finding is not surprising, as these two scores are directly related, as discussed in section 4.1. The fact that these scores are not correlated with the lexical diversity score among children with CI indicates a specific relationship between the phonological and morphophonological processing levels, not mediated by differences in overall language development. These observations corroborate the links observed between syntactic comprehension and phonological scores previously noted among Swedish children (Hansson et al., 2017). However, there are links between the lexical diversity index and gender markings in TH children and number markings in CI children, which may reflect effects related to differences in general linguistic level for these scores. The correlation between the phonemic addition score with both the phonological and lexical scores in the CI group also supports this.

The cues of grammatical development in production are very strongly correlated with phonological skills in the CI group and moderately in the TH group. It should be noted that MLUm scores are also correlated with the lexical index only in TH children. This observation further supports the particular interdependence between phonological and MS levels in CI children, whereas TH children seem to see their linguistic measures evolve more conjointly, as evidenced by the positive correlations observed between phonological and lexical scores on other cues, such as the number of uses of the imperfect tense, and the number of reflexive pronouns, and negatively with the number of omissions. TH children with better grammatical skills are also those with better phonological and lexical scores. This profile is not identical in CI children, phonological scores showing moderate to strong positive links with reflexive pronouns and negative correlation with determiner omissions, but not with the lexical score. Only the verb/utterance ratio shows a joint link with both phonology and lexicon. These specific links among CI children between their phonological and morphosyntactic abilities are consistent with phonological theories of MS difficulties proposed to explain the language disorders encountered by children with SLI (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992; Parisse & Maillart, 2008). The phonological difficulties presented here by children with CI, stemming from the perceptual limitations of the CI, more severely affect MS development due to the lack of perceptual and conceptual prominence of grammatical elements in the linguistic input.

The observation of the links between the different scores of the morpheme identification task shows connections between the processing of number markings and MLUm and the verb/utterance ratio in both groups, which is not surprising. The processing of gender markings, on the other hand, is associated with the verb/utterance ratio. A strong link in CI children and a moderate one in TH children is observed between MLUm values and, on the one hand, the scores related to minimal pairs and, on the other hand, the scores related to distinctions between nasal and oral vowels, as well as nasal and nasal vowels, but also more moderately with the score related to phonemic additions. Children who are proficient at discriminating grammatical and lexical items distinguished by nasal vowels, either from each other or from oral vowels, also tend to have higher MLUm values and more complete sentences (containing a verb). These same children also make more pronominal redundancy errors—a type of error that seems positively associated with morphophonological development. Additionally, a link is observed between the processing of nasal and oral vowels and a reduction in the number of determiner omissions before monosyllabic words in both groups. This is not surprising either: both skills can be attributed to better perceptual processing at both the segmental level (discrimination of nasal and oral vowels—fine spectral processing) and the suprasegmental level (presence of determiners before monosyllabic words—prosodic bootstrapping) in line with Moreno-Torres & Moruno-López (2014).

These various results seem to support the hypothesis of variability in MS performance that can be explained by different degrees of perceptual processing in children with CIs. Indeed, several studies have shown evidenced variability in performance in the discrimination and production of nasal and oral vowels among these children. The ability to adequately exploit cues related to nasal resonance has also been shown to be positively correlated with phonological development in a subgroup of children (Fagniart et al., 2024b), some of whom are included in the present study.

4.4. Individual and environmental factors

Different individual factors have also been studied, such as exposure to Cued Speech (CS) among the children in the CI group, with one group not exposed to it (CS0), another group exposed occasionally (CS-), and a group exposed early and intensively (CS+). The results obtained were rather surprising. One might have expected a positive effect of the CS across all measures, with gradually increasing performances between CS0, CS-, and CS+. Indeed, the use of this manual code, which visually represents all the phonological contrasts of the language, has shown a beneficial effect on receptive (Van Bogaert et al., 2023) and productive skills (Machart et al., 2024), as well as on lexical (Fagniart et al., 2024b; Moreno-Torres & Torres, 2008) and MS skills (Hawes, 2004). However, the results in this study are more inconsistent. Specifically, the group with occasional exposure (CS-) stands out distinctly from the other two groups across almost all the evaluated components. In fact, the children in this group show the lowest performances in the morpho-phonemic processing of items that differ by nasal and oral vowels, obtain a lower verb/utterances ratio, produce fewer reflexive pronouns, conjunctions and possessive determiners, use the past simple tense less frequently, and make more agreement errors between determiners and nouns in terms of gender. On the other hand, they achieve a higher lexical diversity score than the other groups, produce more demonstrative pronouns, and make fewer erroneous additions of function words.

These various results, in light of the different elements of literature discussed above, suggest a developmental profile that is more focused on surface aspects—with greater ease in vocabulary development and the acquisition of more easily lexicalized function words (demonstratives), while experiencing significant difficulties in MS development (more verb-less utterances, poor verbal and lexical morphology). Referring to the dual-route model (Hickok & Poeppel, 2004) mentioned by Moreno-Torres for the CI population, these performances suggest a preferential use of the ventral pathway for information processing, which is more focused on lexico-semantic acquisition, to the detriment of the dorsal pathway, which is focused on segmental development. It may seem contradictory that these same children scored better in phonological production, although this is not incompatible since this measure was taken within the context of a picture-naming task, involving isolated target words. Given the good lexical performances of these children, it is possible that the words in the task, which are of low acquisition age, benefit from good overall phonological representations. However, the processing skills of these children do not seem sufficient to perceive fine phonetic details in the auditory signal, as evidenced by their lower performances in distinguishing nasal and oral vowels. It therefore seems that occasional exposure to CS is not sufficient to help the perceptual system adapt and compensate for the limitations of the CI in exploiting relevant acoustic cues that are better encoded by the CI. This is in line with recommendations regarding the use of CS in French (Charlier, 2020): a necessary condition for linguistic development facilitated by CS is sustained and almost daily coding frequency, with favorable conditions being early exposure (before 18 months) and within family interactions—conditions met by the children in the CS+ group. These findings are consistent with previous studies on the perception and production of nasal and oral vowels, in which children with occasional exposure to CS were significantly less proficient than their peers with intensive and early exposure (Fagniart et al., 2024a; Fagniart et al., in press).

However, it is surprising to observe only a few differences between the group not exposed to CS (CS0) and the CS+ group. Indeed, apart from higher use of prepositions and pronouns in the CS+ group, we did not observe significant differences in the performances of the two groups, either in the sub-scores reflecting perceptual skills in nasal-oral vowel discrimination or in general linguistic performance. The benefits of early and sustained exposure to a method that highlights the multimodality of speech perception are notable in the CS+ group, but they do not seem to be the only sources favorable to higher linguistic development. Since the groups were equivalent in terms of chronological and auditory ages and implantation age, we did not identify any characteristics of the children in this group that could explain their high performances. As mentioned previously, children with CI have more difficulty with implicit learning and are therefore more dependent on environmental conditions: it is possible that variables not controlled for in this study, such as the level of parental involvement (Holzinger et al., 2020; Moeller et al., 2013), the level of linguistic stimulation, or additional therapeutic methods, may have played a role.

The effects of implantation age observed in the study support the positive impact of early implantation, in this case before 18 months. Indeed, children with later implantation showed lower occurrence values of more complex MS markers, such as reflexive pronouns, the use of the past simple tense. Additionally, children with later implantation scored lower in processing items that differed by nasal and oral vowels, as well as having a lower lexical diversity index. The beneficial effect of early implantation is thus evident across various components of language, which can be explained by effective electro-acoustic stimulation during the sensitive periods of linguistic development in line with some previous studies (Gao et al., 2021, 2021; Karltorp et al., 2020; Sharma et al., 2020; Tamati et al., 2022).

The effects of chronological age for the TH group and auditory age for the CI group showed more varied results. Indeed, in many of the evaluated domains, the performance of children in the TH group increased with age, whereas this increase was not as consistent in the CI group. Indeed, the intermediate age group (3;7-4;6 years) showed lower performances than both the younger (2;6-3;6 years) and older (4;7-7 years) groups. This was observed in phonological production scores, scores related to the processing of minimal pairs and nasal/oral vowels and the number of determiner omissions. It should be highlighted that these age effects should, of course, be interpreted with caution: the experimental design was not longitudinal, so the different age groups are independent and may therefore suffer from uncontrolled inter-individual variability, leading to effects not related to maturation. This seems to be the case among the CI group: no factor controlled in the study could identify the reasons for the lower performances observed in this age group—especially since this effect is not consistent across the different tests. Nevertheless, the expected auditory age effects were observed for the number of verbs per utterance, the lexical diversity index, and the use of different verb tenses.

The socio-economic status (SES) of the parents was controlled and tested across our different variables, as this factor has shown an impact on language outcomes (Geers et al., 2009; Huber & Kipman, 2012; Szagun & Stumper, 2012) as well as on early grammatical acquisition (Le Normand & Moreno-Torres, 2014) in children with CI. Our study did not support these findings, as no SES effect was observed among the children in the CI group in the evaluated linguistic components. It is possible that the age range targeted for the study, which is older than that of Le Normand's study, might partially explain these results. As children grow older, they may become less dependent on their family environment in favor of interactions in school or recreational activities. It is also possible that parental education was not a determining factor reflecting more favorable conditions for language stimulation in our sample: indeed, the level of education has been shown to have mixed and heterogeneous effects across studies (Holzinger et al., 2020).

4.5. Limitations

Although this study has allowed for the formulation of numerous findings in connection with the literature, it suffers from various limitations that are important to put into perspective. The first potential bias of the study is the limited sample size, which is characteristic of studies involving CI users. It is indeed complex to recruit a relatively homogeneous but also contrasting sample encompassing all the variables of interest (here, exposure to CS, implantation age, chronological/auditory age). The inter-individual variability characteristic of the CI population complicates the interpretation of the various observed effects, especially given the small sample sizes. Moreover, it would be interesting to replicate this type of study to investigate different language components jointly but in a longitudinal manner, to obtain more reliable developmental data. Different environmental variables could be controlled in studies of this type, such as parental involvement or parenting practices known to have a positive impact on language development.

5. Conclusions

This study allowed for the examination of the connections between phonological and morphosyntactic components in children with CI, with a focus on the processing skills related to the phonological feature of vowel nasality in French.

Several findings were made:

- Morphological processing difficulties were observed in children with CI in items involving phonological contrasts between nasal and oral vowels;
- Children with CI produced shorter MLU (Mean Length of Utterance), fewer complete sentences, and fewer complex function words in their narratives compared to children in the TH group;
- A specific link was observed between phonological and morphosyntactic skills in children with CI;
- Significant variability in performance was observed, with a positive impact of implantation occurring before 16 months, as well as an impact of different language rehabilitation methods.

These findings highlight the importance of early efforts to establish a stable and complete phonological system by implementing specific rehabilitation methods tailored to the perceptual limitations of children with CI. In this regard, early and sustained exposure to CS showed beneficial results in this study. Underspecified phonological representations, associated with a processing mode more focused on salient lexical elements of language, can potentially lead to significant linguistic difficulties.

Chapter 7 Phonetic, phonological, morphologic, lexical and morphosyntactic skills: an integrative study

This final study aims to link the production profiles of the various segments, as investigated in Chapter 5, with the phonological, lexical, and morphosyntactic skills described in Chapter 6, using factor analyses and hierarchical classification analysis. This approach allows children to be ranked according to their overall acoustic and linguistic performances, thereby observing their similarities and dissimilarities. This study includes an initial analysis of all the children recruited during the second data collection, namely 23 children with cochlear implants and 47 children with typical hearing. Unlike in Study 6 (previous chapter), the four children with a bilingual family background have been included. Indeed, since the study consists of individual profile analyses, it will be easier to observe whether these children show performances differing from those of monolingual children without biasing group comparisons. A second analysis presents the performances of a subgroup of children with cochlear implants who underwent the same assessment one year apart, allowing for a longitudinal comparison. The analyses presented in this chapter have not yet been compiled into a manuscript submitted for publication.

1. Introduction

Language skills of children with cochlear implants (CI) have been extensively examined to determine whether they can reach the language level of their peers with typical hearing. These studies report varied findings across different components of language: performances below those of children with typical hearing are frequently reported in the phonological (Bouton et al., 2012; Gaul Bouchard et al., 2007) and morphosyntactic (Bourdin et al., 2016; Caselli et al., 2012; Duchesne et al., 2009; Le Normand & Thai-Van, 2023) domains, with, however, significant variability. Lexical development is more often reported as being less affected (Caselli et al., 2012; Duchesne et al., 2009; Rinaldi et al., 2013). These variable linguistic performances can be explained, on the one hand, by delayed access to oral input during the pre-implantation phase, but also by the perceptual limitations related to sound processing by the CI (see chapter X, section X for more details). The perceptual limitations are likely to have a greater impact on certain speech sounds carried by fine-grained acoustic cues, such as vowel nasalization (Borel, 2015; Bouton et al., 2012; Fagniart et al., 2024a) or consonant places of articulation (Bouton et al., 2012; Cheng & Chen, 2020; Medina et al., 2004; Peng et al., 2019), particularly when they are carried by acoustic information in the high-frequency ranges like fricative consonants (Grandon, 2016; Mildner et al., 2006; Reidy et al., 2017; Todd et al., 2011; Warner-Czyz & Davis, 2008). However, despite these perceptual limitations, a majority of children with CI manage to form phonological representations of vulnerable acoustic features, as evidenced by their above-chance abilities in identifying and discriminating nasal and oral vowels and an almost equivalent (sometimes even superior) level of intelligibility compared to same-age peers (Fagniart et al., in press). Children with CI, having had to build their phonological representations based on limited oral input, may have relied more on acoustic cues that are better transmitted by the CI, such as temporal cues or formant frequency cues—as long as the peak frequencies are not too close and/or high - particularly when these cues are accompanied by visible articulatory gestures (lip rounding, aperture). Additionally, variability was also noted in the perception of vowel nasalization (Fagniart et al., 2024a) and in the use of production mechanisms for the nasal-oral distinction related to nasal resonance cues (Fagniart et al., in press). Moreover, better mastery of the nasal-oral distinction through nasal resonance was also positively correlated with the overall phonological level in a previous study (Fagniart et al., 2024b).

In this context, it is not surprising to observe significant variability in performance. The development of lexical and morphosyntactic components, which relies on the memorization of precise and appropriate phonological forms, may be hindered by under-specified phonological and phonetic representations. The increased vulnerability of the morphosyntactic component compared to the lexical level and the close links between phonological and morphosyntactic levels in a population with language difficulties have been seen as reflecting, on the one hand, the lower perceptual salience of grammatical elements in the spoken chain compared to highlighted lexical elements. On the other hand, lexical elements benefit from more concrete conceptual substance and are also easier to teach explicitly (Hage, 2005). These propositions form the basis of phonological theories of morphosyntactic difficulties in children with specific language impairments (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992; Parisse & Maillart, 2008). Convergent findings were made in a previous study on children with CI (see chapter 6): specific correlations between phonological and morphosyntactic levels were observed, with children of the same age with CI showing a correlation between all language levels, including the lexical level.

1.2. Aims of the study

In this context, it seems particularly interesting to attempt to link the specific perceptual difficulties of children with cochlear implants (CI) to their linguistic performance in the phonological, lexical, and morphosyntactic domains. Indeed, the significant variability observed among CI users in their ability to process vulnerable segments could partly explain the variability observed in phonological performance, and, consequently, in morphosyntactic abilities, as the latter depend on a precisely specified phonological representation.

To this end, two groups of children were recruited: one group of children with CI and one group of children with typical hearing, matched by chronological or auditory age. Note that in the present study, perceptual abilities will not be directly investigated but will be assessed through acoustic analyses of the production of segments encompassing a large range of acoustic correlates and posing various challenges for sound transmission through the CI. In this regard, three types of segments will be studied:

- nasal vowels compared to their phonological (/ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/) or phonetic (/ɑ̃/-/ɔ/, /ɑ̃/-/o/, /ɔ̃/-/o/, /ɔ̃/-/u/, /ɛ̃/-/a/) counterparts according to the matching proposed by Borel and used in previous experimental paradigms (Fagniart et al., 2024a; Fagniart et al., in press). Two production strategies for the production of vowel nasalization will be acoustically investigated: the degree of nasal resonance, knowing that the distinction between oro-nasal and oral-only resonance is carried by fine acoustic cues that are highly vulnerable in CI processing; and the specific oropharyngeal configuration of the target vowel through formant measurements, these cues being more likely to be exploited through CI in situations where the vowel's formants are well distinct and associated with visible articulatory dimensions (jaw opening, lip rounding).

- fricative consonants (/f/-/s/-/ʃ/-/v/-/z/-/ʒ/) considered for their specific places of articulation through the study of spectral peaks, as well as for their degree of frication noise through the study of acoustic energy in mid and high frequencies. Indeed, specific difficulties have been observed in differentiating between fricatives places of articulation (Giezen et al., 2010; Hedrick et al., 2011; Lane et al., 2001; Mildner & Liker, 2008; Reidy et al., 2017), but also in exploiting the high-frequency energy in frication noise (Fagniart et al., 2024b, 2024a). These two difficulties directly reflect the perceptual challenges posed by the limited high frequency coding by the CI.
- voiceless stop consonants compared to their voiced counterparts, their distinction being based on temporal acoustic correlates (Voice Onset Time) that are supposed to be well coded by the CI. However, the literature has shown contradictory results (Bouton et al., 2012; Giezen et al., 2010; Grandon et al., 2017; Horga & Liker, 2006; Peng et al., 2019; Uchanski & Geers, 2003), again showing some variability in the ability of children with CI to exploit the cues related to the voicing feature in stops.

The production abilities associated with these different segments, assessed through acoustic measurements, will thus be linked to linguistic performance. Four components will be investigated:

- Morphemic processing abilities in grammatical and lexical contexts through scores in a sentence/word-picture matching task, with particular attention paid to items contrasting nasal and oral vowels.
- The level of phonological development as assessed through a picture naming task.
- Lexical level through the observation of the number of first-attempt retrievals of lexical targets in picture naming, as well as through lexical diversity indices in narrative production.
- Morphosyntactic level by analyzing Mean Length of Utterance (MLU) indices as well as various markers of morphosyntactic complexity within narrative accounts.

Different objectives are pursued:

- To observe the performance of children with CI in comparison to their peers with typical hearing.
- To observe the relationships between the various acoustic and linguistic variables among participants through a factor analysis.
- To determine whether the factor analysis allows for the emergence of performance profiles among the children, which may or may not correspond to their hearing status.

Different potential sources of variability in performance will also be studied in accordance with elements from the literature, namely:

- Chronological/auditory age,
- The socioeconomic status of the parents,
- The age of implantation,
- The level of exposure to Cued Speech.

2. Method

2.1. Participants

A group of children with typical hearing (TH group) and another group of children with cochlear implants (CI group) were recruited for the study. The TH group included 47 monolingual French-speaking children with typical hearing, averaging 56±13 months of age, who did not present any learning delays or auditory disorders. The CI group consisted of 23 French-speaking children (mean age: 67±15 months) with congenital bilateral profound hearing loss. Among them, 22 had bilateral implants, and one child had a unilateral implant. All CI participants underwent oralist auditory rehabilitation, both at their rehabilitation centers and within their family environments. All the children were monolingual French speakers except for four children who came from bilingual family environments: two were French-Portuguese bilinguals, and two were French-Arabic bilinguals. The CI group was divided based on their exposure to Cued Speech (CS): 8 children had no exposure to CS (CS0), while 15 were exposed to CS during speech therapy sessions (2 to 3 sessions per week) and/or in their family settings (CS1). The group was also categorized by implantation age: those who received their first implant before 16 months were classified as early implantations (CI/EI, n=12), while those implanted after 16 months were classified as late implantations

(CI/LI, n=11). The age of 16 months was selected in alignment with studies indicating significant benefits from implantation before 18 months (Sharma et al., 2020). Based on the distribution of implantation ages, we lowered the threshold to 16 months to create comparable groups in terms of numbers. All participants took part in an initial testing session (T1). The socio-economic status (SES) level of the children was also studied based on the education levels of both parents, by averaging the number of years they had spent in education, following the method of Le Normand (2022) according to Desrosières' classification (Desrosières et al., 1983). Two categories were determined: the high level, which includes education levels between high school and postgraduate degree (CI: N = 15; TH: N = 35), and the low level, which includes education from elementary school to a high school degree (CI: n = 8; TH: n = 12). The entire group of children with cochlear implants was re-contacted to conduct a second testing one year later. Thirteen children from the total sample were available for this second assessment (T2), allowing for a longitudinal comparison of their performance. The list of participants and their characteristics are presented in Table 7.1.

Subject	Sex	Chronological age (months)	Age at first implantation (months)	Implantation age group: early (EI) – late (LI)	Hearing age (months)	Implantation type	CS exposure group	SES level	Bilinguism	T2
CI1	B	54	9	EI	45	Bilateral	CS0	Low	No	No
CI2	B	77	39	LI	38	Bilateral	CS0	Low	No	No
CI3	G	70	15	EI	55	Bilateral	CS0	Low	No	No
CI4	G	79	7	EI	72	Bilateral	CS0	High	No	No
CI5	G	78	31	LI	57	Unilateral	CS+	Low	No	No
CI6	G	55	7	EI	48	Bilateral	CS+	High	No	No
CI7	G	87	13	EI	74	Bilateral	CS-	Low	No	No
CI8	B	55	13	EI	42	Bilateral	CS-	Low	No	No
CI9	B	57	13	EI	44	Bilateral	CS+	High	No	Yes
CI10	B	54	12	EI	42	Bilateral	CS-	High	No	Yes
CI11	G	54	18	LI	36	Bilateral	CS-	Low	No	Yes
CI12	B	66	9	EI	57	Bilateral	CS-	High	Yes	Yes
CI13	G	87	24	LI	63	Bilateral	CS-	High	Yes	Yes
CI14	G	94	26	LI	68	Bilateral	CS-	Low	Yes	Yes
C15	G	83	23	LI	60	Bilateral	CS-	Low	Yes	Yes
C16	G	81	20	LI	61	Bilateral	CS+	High	No	Yes
C17	B	72	20	LI	52	Bilateral	CS0	Low	No	No
CI18	G	45	23	LI	22	Bilateral	CS0	Low	No	Yes
CI19	G	60	12	EI	48	Bilateral	CS+	Low	No	No
CI20	G	44	32	LI	12	Bilateral	CS-	Low	No	Yes
CI21	B	59	11	EI	48	Bilateral	CS0	High	No	Yes
CI22	G	79	17	LI	62	Bilateral	CS+	Low	No	Yes
CI23	G	60	13	EI	47	Bilateral	CS+	Low	No	Yes

Table 7.1: Characteristics of the CI children.

2.2. Tasks

2.2.1. Naming task

A picture-naming task was first proposed to the children. Forty-eight target words were selected in the construction of this task to ensure the inclusion of all French phonemes in initial, medial, and final syllable positions. These words were also chosen for their early age of acquisition (based on Chalard et al., 2003) to facilitate retrieval by the children (for more details, see Philippart De Foy et al., 2018). The list of target words used in the task can be found in Appendix 3.

The target word pictures were presented one at a time in a booklet, and the child was asked to name each picture orally. If the child did not respond or if the word produced did not match the target (e.g., semantic paraphasia or a random response), different prompts were provided. First, semantic cues related to the target word were given (e.g., "you can use it when it rains" for /paʁaplɥi/ - umbrella). If the target word was still not produced, a phonological cue was provided by giving the initial phoneme (e.g., "it starts with /s/" for /suri/ - mouse). If these two cues were insufficient for the child to retrieve the target word, the experimenter would say the word and ask the child to repeat it.

2.2.2. Sentence/word-picture matching task (SWPMT)

A comprehension task followed, consisting of a sentence/word-picture matching activity. A word or short sentence was presented auditorily to the child through audio recordings, and the child was then asked to point to the corresponding picture between the target image and a distractor. The distractors were chosen to form a minimal pair with the target. The task included a total of 28 items. The differences between the target words/sentences and their distractors involved : 13 number markings (e.g., "il va" - /il va/ (he goes) vs. "ils vont" - /il vɔ̃/ (they go)], 7 gender markings (e.g., "boulanger" - /bulɑ̃ʒe/ (baker – male) vs. "boulangère" - /bulɑ̃ʒɛʁ/ (baker – female)] and 8 minimal pair variations [e.g., "bain" - /bɛ̃/ (bath) vs. "banc" - /bɑ̃/ (bench)]. These different grammatical and lexical distinctions were reflected in various phonological contrasts: oral/nasal (n= 10), oral/oral (n= 3), or nasal/nasal (n= 3) vowel substitutions, as well as phonemic additions (n= 12). The list of items and an illustration of the testing interface are available in Appendix 4.

The children were presented with two images (the target image and the distractor) on a tablet. They listened to the target word or sentence through an audio recording played via loudspeakers (Bose Soundlike). The sound level was controlled to reach an average level of 60 dB. The children were then asked to point to the corresponding target image among the two images. Five practice items were provided before the task to ensure the children understood the instructions and to adjust the sound volume for optimal listening of the stimuli.

2.2.3. Narrative production tasks

Two narrative production tasks were proposed to the children: an induced narrative task and a free narrative task.

The first narrative task was the induced narrative. Initially, a story with animations was presented to the children. This animated story was shown on a tablet, where the animations illustrated the story to provide visual support, while a recorded narrator told the story. To ensure that the child did not focus solely on the narrator or the animations and miss important information, the narration and animation phases alternated without overlapping, allowing the child to switch between them. After the complete presentation of the story, the child was asked to retell the story using the previously shown animated images as visual support. The purpose of the induction phase was to present a story containing various twists and turns that introduced various verbal tenses et modes (past, future, conditional), as well as gender and number markers, to encourage varied productions of grammatical markers and verb forms from the children. The full elicited narrative, along with an illustration of the presentation interface, is available in Appendix 5.

The free narrative task involved presenting the wordless picture book frequently used in clinical practice and research, “Frog, Where Are You?” (Mayer, 1969). The child was shown the book and asked to tell the story.

2.3. Procedures

The children completed the four tasks in a quiet environment, accompanied by the experimenter and, in some cases, their speech therapist. The tasks were administered in the following order: first, the picture-naming task, followed by the induced narrative production task, the comprehension task, and finally, the free narrative production task. The total testing time ranged between 35 and 60 minutes, with breaks offered to the children between tasks. All of the children’s productions were recorded using an H5 Zoom portable audio recorder, and the responses to the sentence/word picture-matching task were noted during the session. The tests conducted with the subgroup of 13 children, one year apart, were carried out in the same manner.

2.4. Measures

Various measures were collected to describe the production profiles in terms of acoustic features and phonological, morphological, lexical, and morphosyntactic components. The different measures, described below, were averaged per subject to enable the performance of factorial analyses representing each child on the dimensions extracted from the set of measures.

2.4.1. Acoustic measures

The complete description of the collected measures and the semi-automated analysis procedure of the audio signals is provided in Chapter 3, 4 and 5 and will only be partially described in this section.

The acoustic description of vowels aimed to study the two main aspects of nasal/oral vowel production: the adoption of an articulatory configuration specific to the vowel quality, on one hand, and the resonance with the nasal cavities (only for nasal vowels) on the other hand. To investigate the acoustic characteristics associated with oropharyngeal configuration, formant values were examined. For the study of nasal resonance, Nasalization from Acoustic Features (NAF) values (Carignan et al., 2023) were generated. A total of 6605 vowels were analyzed. To investigate the strategies used in the phonetic implementation of the phonological contrast between nasal and oral vowels, paired comparison analyses were conducted. These analyses considered the phonetic (/ɑ̃/-/ɔ/, /ɑ̃/-/o/, /ɔ̃/-/o/, /ɔ̃/-/ɔ/, /ɔ̃/-/u/, /ɛ̃/-/a/) and phonological (/ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/) proximity of oral-nasal pairs in French (Borel, 2015). For each child, each produced nasal vowel was paired with all orally produced vowels that were phonetically or phonologically similar, resulting in a listing of all oral/nasal pairs produced. A total of 30,402 pairs were formed, allowing for comparisons of acoustic cues within each nasal-oral pair. Euclidean distances in the F1-F2-F3 (Bark) planes and differences between NAF values were examined for each pair. In the present study, two measures were selected for inclusion in the factor analyses:

- The Euclidean distances on the F1-F2-F3 plane between phonological and phonetic nasal-oral pairs.
- The NAF value differences between phonological and phonetic nasal-oral pairs.

The acoustic characterization of fricative consonants was conducted using recently developed measures (Shadle et al., 2023), which allowed for the identification of spectral peaks related to the place of articulation for each segment, i.e., the location of airflow obstruction, and the quality of the frication noise by analyzing intensity ratios across low, mid, and high-frequency bands. A total of 1,917 fricatives were analyzed. Three measures were selected for the factor analyses:

- Spectral peak differences between anterior (/f/-/v/) and median (/s/-/z/) fricatives, and between median and posterior (/ʃ/-/ʒ/) fricatives, to reflect the distinction between the three places of articulation.

- AmpDiff values, which represent the energy ratio between low- and mid-frequency ranges of the frication noise.
- LevelD values, which represent the energy ratio between mid- and high-frequency ranges of the frication noise.

A “good” frication noise source should have a significant portion of acoustic energy in the mid and, particularly, high frequencies. Therefore, a good noise source should result in high AmpDiff values (as mid frequencies are reinforced compared to lows) and low LevelD values (indicating a large proportion of energy in high frequencies).

For the acoustic characterization of the voicing feature in stop consonants, Voice Onset Time (VOT) measurements were conducted. A total of 3,012 stops were analyzed. For the study, a composite measure was created by calculating the difference between the average VOT values of voiced stops and the average VOT values of voiceless stops.

2.4.2. Phonological score

The children’s productions in the naming task were initially annotated by an examiner and subsequently verified by the first author using the Phon 3.1 software (Hedlung & Rose, 2020). The software compared the target phonological form with the actual annotated production, enabling the extraction of various phonological accuracy scores. In this study, we will focus exclusively on a global score of the percentage of correct phonemes (PCP).

2.4.3. Sentence/word-picture matching task scores

In the sentence/word-picture matching task scores, *d’* scores were computed for all types of grammatical markers involved: gender and number, as well as for minimal pairs. These scores also accounted for the different phonological mechanisms underlying the contrasts between the target and the distractor, such as contrasts between nasal and oral vowels, oral and oral vowels, nasal and nasal vowels, or phonemic addition. The d’ scores were calculated by subtracting the normalized, centered, and standardized values of the hit rate (correct detection) and the false alarm rate (incorrect detection), following signal detection theory (MacMillan & Creelman, 1991). Extreme values of 0 and 1 were adjusted to 0.01 and 0.99, respectively, to facilitate Z-score conversion. For the factorial analyses, the total score for all items, as well as the scores specifically targeting items that contrasted based on a morphophonological alternation between oral and nasal vowels, were used.

2.4.4. Narrative production scores and error types

The children's narrative productions, captured in audio recordings, were transcribed using PHON (Hedlung & Rose, 2020) and then exported to the Computerized Language Analysis (CLAN) software (MacWhinney, 2000). This allowed for a morphosyntactic annotation of the words in the narratives using the MOR and POST functions (Parisse & Le Normand, 2000). The KidEval program was employed to extract various indices of morphosyntactic development and to categorize the different function words and verb tenses used.

Within the factorial analyses, we included the following cues:

- Mean Length of Utterance (MLU) in morphemes (MLUm). This index is commonly used to assess the level of morphosyntactic development and has also shown significant differences between the CI and TH groups in the previous study (chapter 6).
- The number of reflexive pronouns. This complex function word demonstrated effects related to both auditory status (CI vs. TH) and exposure to CS, as well as the age at which the CI was implanted (chapter 6).
- The frequency of past simple tense usage among verbs. Indeed, the imperfect tense requires the use of bound grammatical morphemes, and differences in its usage were observed between our groups in the previous study.

Various types of errors were identified and categorized by the first author of the article. In the factorial analyses conducted, only errors related to the deletion of determiners before monosyllabic versus bisyllabic nouns were retained. Indeed, these errors were previously found to be significantly more frequent in the CI group and were influenced by the age at which the CI was implanted and the exposure to CS.

We also included a measure of lexical diversity, the D index, obtained using the VOCD procedure in CLAN. This index provides a probability of introducing a new word as the length of a corpus increases, allowing for a value that is not influenced by the corpus size (Duran et al., 2004).

2.5. Statistical analysis

Multiple factor analyses were performed using the FactoMineR package (Husson et al., 2024), and graphical representations were generated with Factoextra (Kassambara & Mundt, 2020). These analyses were conducted on a dataset containing subject-wise averages of various acoustic measures, aggregated as means and converted into z-scores, including:

- Variables related to the marking of the distinction between nasal and oral vowels: averages of the differences between all phonologically and phonetically paired nasal-oral vowel pairs on indices related to nasal resonance (NAF) (NAF_phono and NAF_phone in the model) and on the Euclidean distances in the F1, F2, F3 plane (F123_phono and F123_phone).
- Variables related to the distinction of fricative places of articulation: differences in the average spectral peak values between anterior fricatives /f-v/ and medial fricatives /s-z/ (SP_1_2), and between medial fricatives /s-z/ and posterior fricatives /ʃ-ʒ/ (SP_2_3).
- Variables related to the representation of average and high frequency ranges in frication: average values of the ampDiff and levelD ratios.
- Variable related to the distinction between voiced and voiceless plosive consonants in terms of VOT: VOT_UV_V.
- Variables related to morphemic processing, including the total score on the sentence/word picture-matching task (SWPM_tot) and the score for items specifically contrasted by a morphophonological alternation between oral and nasal vowels (SWPM_or_nas).
- Variables related to performance in picture naming tasks: the average percentage of correct phonemes in naming (PCP) and the percentage of first-attempt elicitation (Naming).
- Variables related to performance in narrative tasks: the mean length of utterance in morphemes (MLUm), the lexical diversity index (*D* index), the number of uses of the imperfect tense (Simple_past), the number of reflexive pronouns (Refl_pro), the number of determiner omissions before one-syllable words (Det_del_1syll) and two-syllable words (Det_del_2syll).

The children's characteristics were added to the models as supplementary variables, without influencing the construction of the dimensions, to enable the observation of the characteristics of individuals positioned along the different dimensions. After establishing the dimensions in the factorial analysis, hierarchical ascending classifications (Husson et al., 2024) were performed to form clusters related to the children's performance, as summarized across the different axes. This method involves establishing dissimilarity indices between individuals and an aggregation index between classes of individuals, resulting in a dendrogram that represents the ascendant grouping of individuals. This approach was chosen to classify various performance profiles of the children independently of their auditory status. The classification was based on the first three dimensions of the factor analysis, representing 52.9% of the explained variance. The resulting hierarchical tree (dendogram) was used to determine an optimal cut-off point, allowing for the selection of groups that balances differentiating the overall group without being overly simplistic according to a method described by Cornillon et al. (2018).

To identify the profiles of the different clusters formed, group comparison analyses were conducted using generalized linear mixed models, controlling for the random effect associated with the subject, employing the lme4 package (version 1.1-34; Bates et al., 2015) and emmeans package (Lenth et al., 2023) within the R software (R Core Team, 2022).

3. Results

3.1. Results at T1

3.1.1 Principal components analysis (PCA)

The factor analysis extracted 19 dimensions corresponding to the number of variables implemented in the model. Only the first three dimensions, accounting for 52.9% of the cumulative variance, will be described. Figure 7.1 illustrates the contribution of the different variables within the three dimensions The correlation values between the different variables and each of the three dimensions are available in Appendix 8.

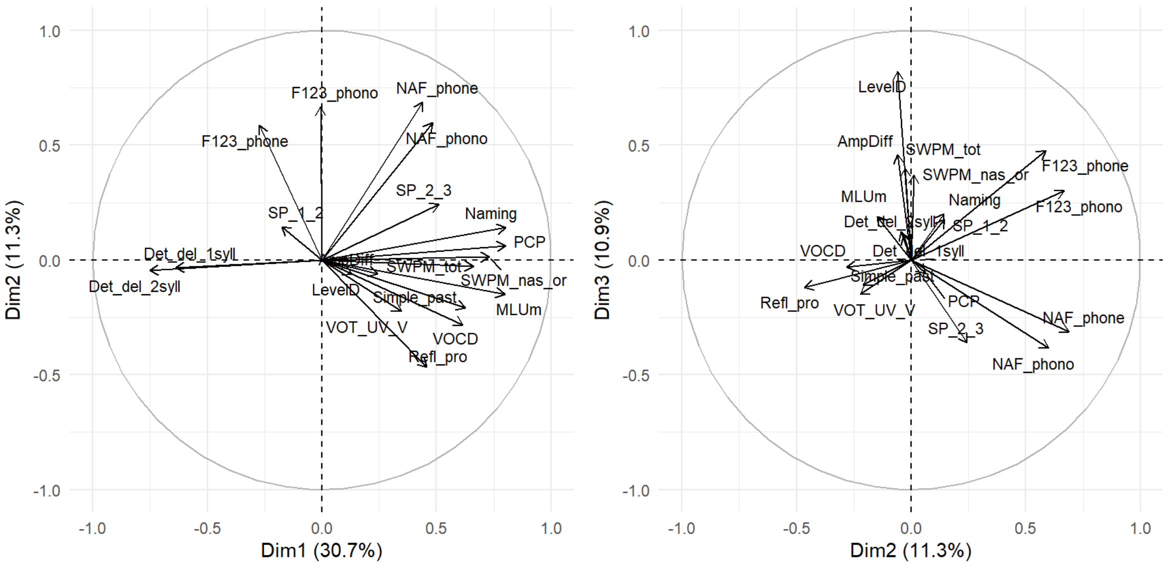

Figure 7.1: Correlation circle of the initial variables for dimensions 1 and 2 (left) and 2 and 3 (right), according to their degree of contribution to the construction of the axes (indicated by the length of the arrows).

Dimension 1, representing 30.7% of the explained variance, appeared to be directly related to performance in linguistic tasks. Indeed, the variables most contributing to the positive values of the axis are MLUm (0.8), PCP (0.8), the number of spontaneous naming in the naming task (0.8) and the sentence/word-picture matching task score related to nasal and oral vowels (0.73), Strong correlations with Dimension 1 were also observed for the lexical diversity score D (0.61) and the use of the imperfect tense (0.62). On the negative values of the axis, the deletion of articles for one-syllable (-0.64) and two-syllable (-0.75) words were the most significant contributors. Dimension 2, representing 11.3% of the explained variance, was directly associated with the acoustic marking of the distinction between nasal and oral vowels. The most contributing variables on the positive values of the axis are those related to NAF values (NAF_phono: 0.59, NAF_phone: 0.69) and the values related to Euclidean distances in F1-F2-F3 (F123_phono: 0.67, F123_phone: 0.59). Dimension 3 (10.9% of the explained variance) was associated on its positive values primarily with high average values of the levelD ratio (0.82) and, to a lesser extent, ampDiff (0.45), as well as with the marking of the nasal-oral distinction through Euclidean distances in F1-F2-F3 (F123_phono: 0.3, F123_phone: 0.47). On the other hand, Dimension 3 was negatively associated with the marking by the NAF index (NAF_phono: -0.38, NAF_phone: -0.31) and the distinction of the medial and posterior places of articulation of fricatives (SP2_3: -0.36).

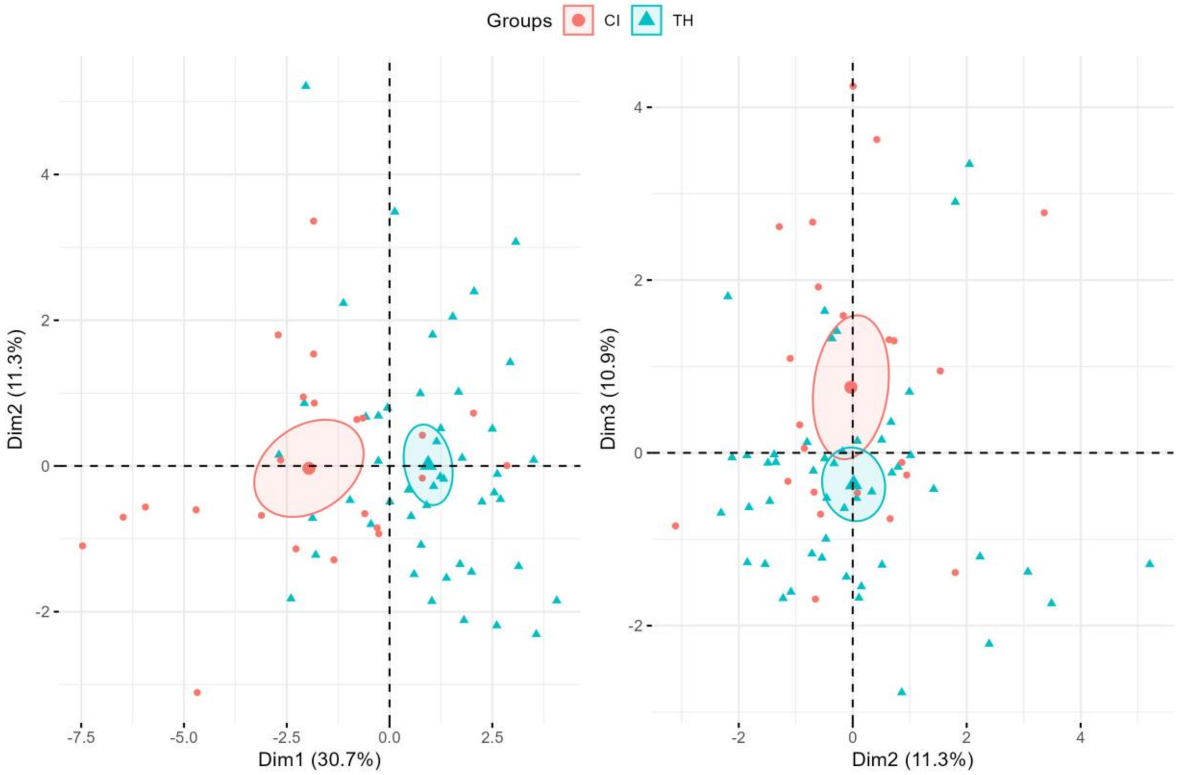

Figure 7.2: Individual plots according to dimensions 1 and 2 (left) and 2 and 3 (right) based on the CI and TH groups with associated 95% confidence interval ellipses.

Figure 7.2 displays a clear tendency for the CI group of children to position themselves on the negative side of Dimension 1 compared to the TH group (on the positive side), indicating lower values across the linguistic scores. Dimension 2 did not appear to discriminate between the groups, with both groups tending to position near zero. The distribution of the groups on Dimension 2 and Dimension

3 showed a clear tendency on Dimension 3, with the CI group positioning more on the positive side, indicating a stronger marking of nasal-oral vowels based on the F1-F2-F3 Euclidean distance indices and higher values of the levelD and ampDiff ratios. However, it is important to note an important variability in the distribution of children within the CI group. Figure 7.3 represents 95% confidence interval ellipses around the groups formed by the different levels of exposure to CS and the age of implantation.

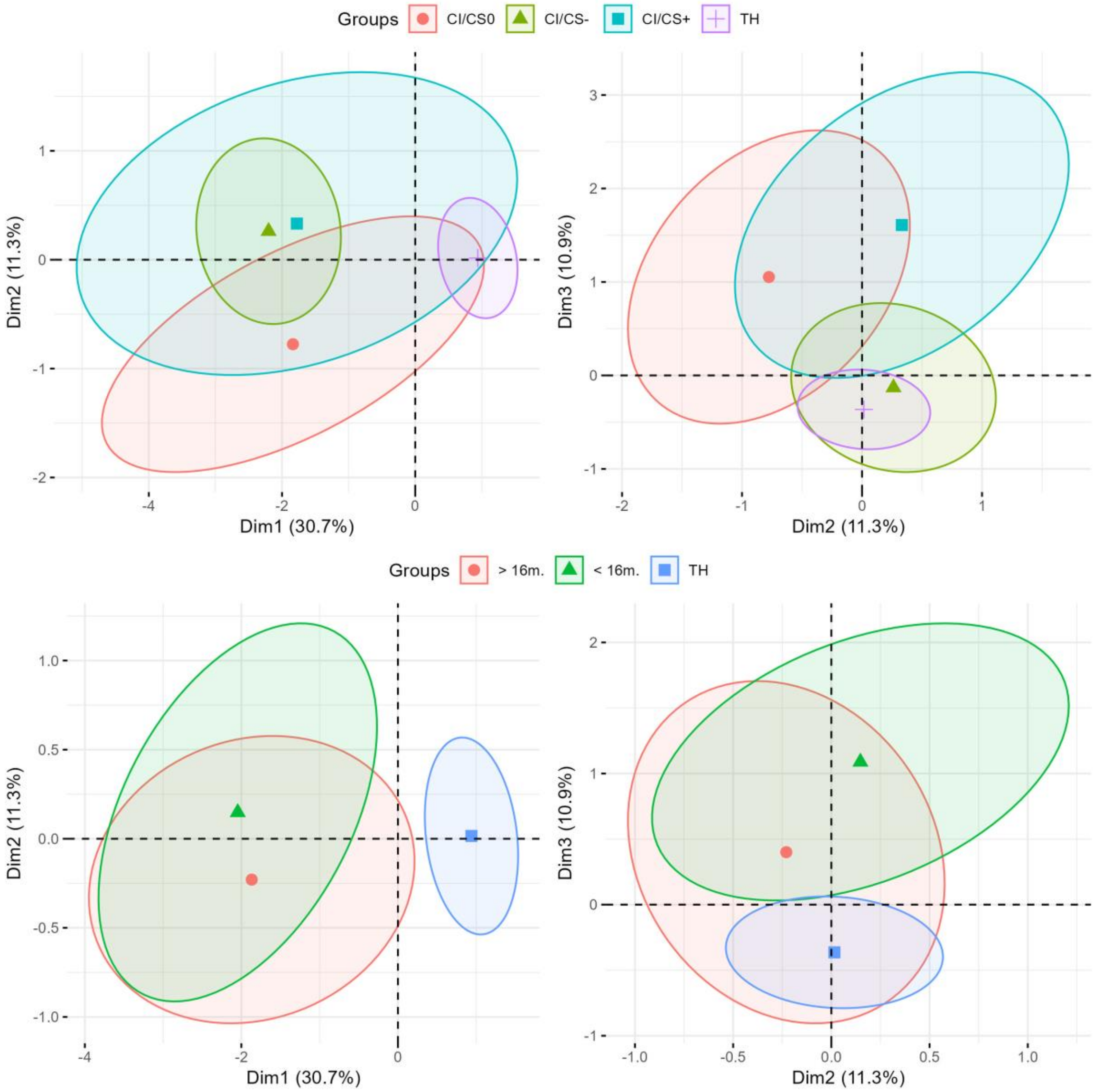

Figure 7.3: Plots of individuals representing 95% confidence interval ellipses around the mean values of the groups, based on exposure to CS (top graphs) and age of implantation (bottom graphs), according to dimensions 1 and 2 (left side) and dimensions 2 and 3 (right side).

Regarding the level of exposure to CS, the different groups of CI children did not distinguish themselves on Dimension 1, but show slight differences on the other dimensions: the CS- and TH groups are, on average, positioned at similar levels on Dimensions 2 and 3, with mean values close to the zero axes, while the CS0 group was found in the negative values on Dimension 2 and intermediate compared to CS+ in the positive values on Dimension 3. Regarding the age of implantation groups, the CI groups again did not distinguish themselves on Dimension 1, but they do on Dimensions 2 and 3, with the late implantation group (>16m) positioned more in the negative values on Dimension 2, and the early implantation group having the most positive values on Dimension 3.

3.1.2. Hierarchical Ascendant Classification (HAC)

To precisely categorize the different profiles of performance in terms of acoustic and linguistic production, unsupervised classification analyses, specifically hierarchical clustering, were conducted using the three dimensions of the factorial analysis. A significant drop in inertia gain was observed at a height of 0.7, where the dendrogram splits the sample into four clusters, as illustrated in Figure 7.4.

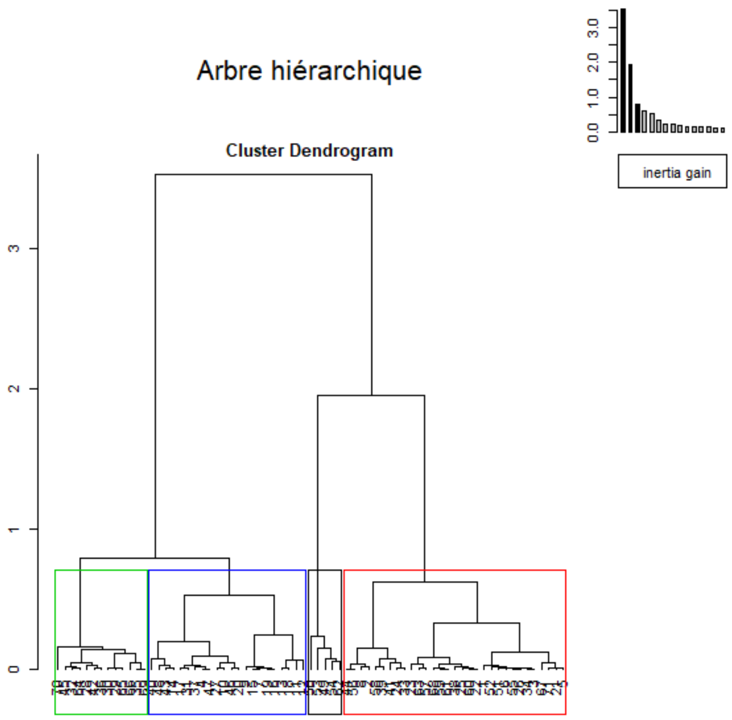

Figure 7.4: Dendrogram of the hierarchical ascending classification (left) and graph showing the distribution of inertia related to the cut-off heights (top right).

Figure 7.5 illustrates the distribution of the four clusters highlighted by the HAC thus constituted along axes 1, 2 and 3 of the PCA.

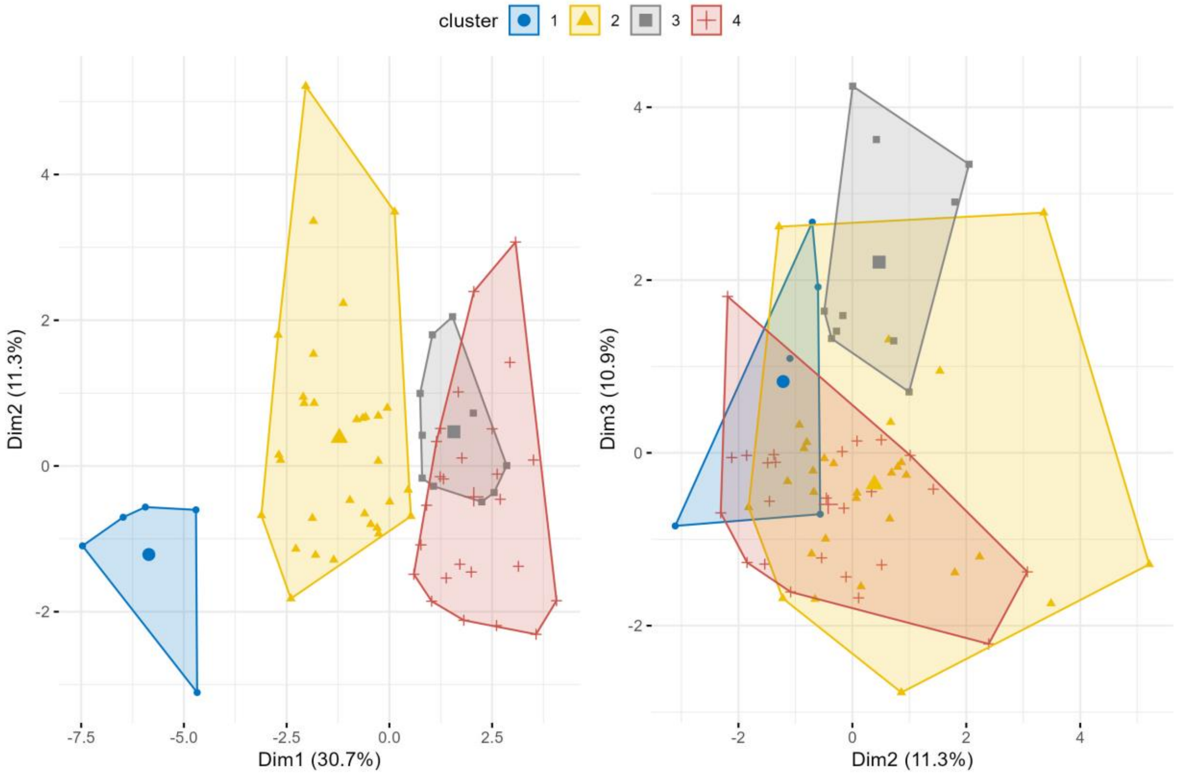

Figure 7.5: Distribution of the 4 clusters along PCA dimensions 1 and 2 (left) and dimensions 2 and 3 (right).

Cluster 1 was clearly set apart from the other groups on Dim 1 and therefore seems to be associated with the lowest linguistic performance, while Cluster 2 was in an intermediate position, with Clusters 3 and 4 being clearly positioned on the right side of the Dim 1 axis in a similar manner. Cluster 1 also distinguished itself from the other clusters by positioning in the negative values of axis 2, while the other clusters were located near zero. The clusters showed distinct tendencies on Dim 3: clusters 1 and 3 were positioned in the positive values, with cluster 3 to a greater extent, and cluster 4 in the negative values. Cluster 2 exhibited significant variability on Dim 3.

To identify the characteristics of the children from the different clusters, various variables were analyzed. Table 7.2 shows the counts based on auditory status and the average ages of each group, along with the p-values from the associated Chi-square independence test or Kruskal-Wallis test.

Variable	Groups	Cluster 1	Cluster 2	Cluster 3	Cluster 4	p-values (Chi-squared/Kruskal-wallis test)
Auditory status (N)	CI	5	14	4	0	<.001
	TH	0	17	6	25	
	Total	5	31	10	25	
Chronological age (months)	CI	71.6	64.3	72.7	NA	NS
	TH	NA	47.7	54.1	63.5	<.001
	Total	71.6	55.1	61.6	63.5	<.001
Auditory age (months)	CI	49.8	47.4	54.5	NA	NS
	TH	NA	47.7	54.1	63.5	<.001
	Total	49.8	47.4	54.3	63.5	<.001
SES level (N)	Low	4	13	2	8	NS
	High	1	18	8	17	

Table 7.2: Counts or means of the different clusters based on auditory status, chronological and auditory age, and SES with associated group comparison tests (Chi-square or Kruskal-Wallis).

It can be observed that while Cluster 1 was composed only of children from the CI group (n=5), Cluster 4 consisted solely of children from the TH group (n=25). Clusters 2 and 3 had equivalent proportions of children from both groups. In terms of chronological age groups, the children from the TH group were younger in Cluster 2 than in clusters 3 and 4, while the children in Cluster 1 were the oldest in the CI group. In terms of auditory ages, the CI children were statistically equivalent across the three clusters. It is also noteworthy that in Cluster 2, the children from both the CI and TH groups had equivalent auditory ages. Additional Chi-square independence tests were conducted on the children's characteristics to see if any could explain differences between clusters. No effect of gender ($\chi^2(3) = 1.17$; p =.7), presence of bilingualism in the family ($\chi^2(3) = 2.72$; p =.4) or socio-economic status ($\chi^2(1) = 5.7$; p =.12) were found. Characteristics specific to the children in the CI group were also studied within this group (Table 7.3).

Variable	Groups	Cluster 1	Cluster 2	Cluster 3	p-values (Chi-squared)
CS (N)	CS0	2	3	2	NS
	CS-	1	8	0	
	CS+	2	3	2	
Implantation age group (N)	<16m.	2	8	1	NS
	>16m.	3	6	3	

Table 7.3: Counts of the clusters based on CS exposure and implantation age groups among CI children with associated group comparison tests (Chi-square).

The distributions of the children among clusters were equivalent according to the level of exposure to CS ($\chi^2(4) = 5.24$; $p = .3$) and the age of implantation group ($\chi^2(2) = 1.44$; $p = .5$).

To further explore the general findings regarding linguistic performance and production profiles observed through the dimensions of the factor analysis, comparisons of the raw values of the different variables studied were conducted and summarized in Figure 7.6. The analysis of the different scores allows for a more detailed characterization of the four clusters.

Cluster 1: This cluster, composed solely of children with cochlear implants, represented the lowest linguistic performance, with significantly lower values of MLUm (2.92), PCP and number of spontaneous naming compared to the other three clusters. Regarding the lexical diversity index D and the sentence/word-picture matching task scores (total score and items containing nasal-oral oppositions), this cluster had performances equivalent to those of cluster 2 and lower than those of clusters 3 and 4. On the acoustic level, the values marking the nasal-oral distinction were also lower than in the other three clusters for NAF values but are statistically equivalent in terms of F1-F2-F3 Euclidean distances. Concerning the production of fricatives, the average spectral peak values for their medial vs. posterior places of articulation were significantly lower than those of the other clusters. Regarding the VOT values of plosives, the difference between voiced and voiceless plosives was significantly less marked than in cluster 4.

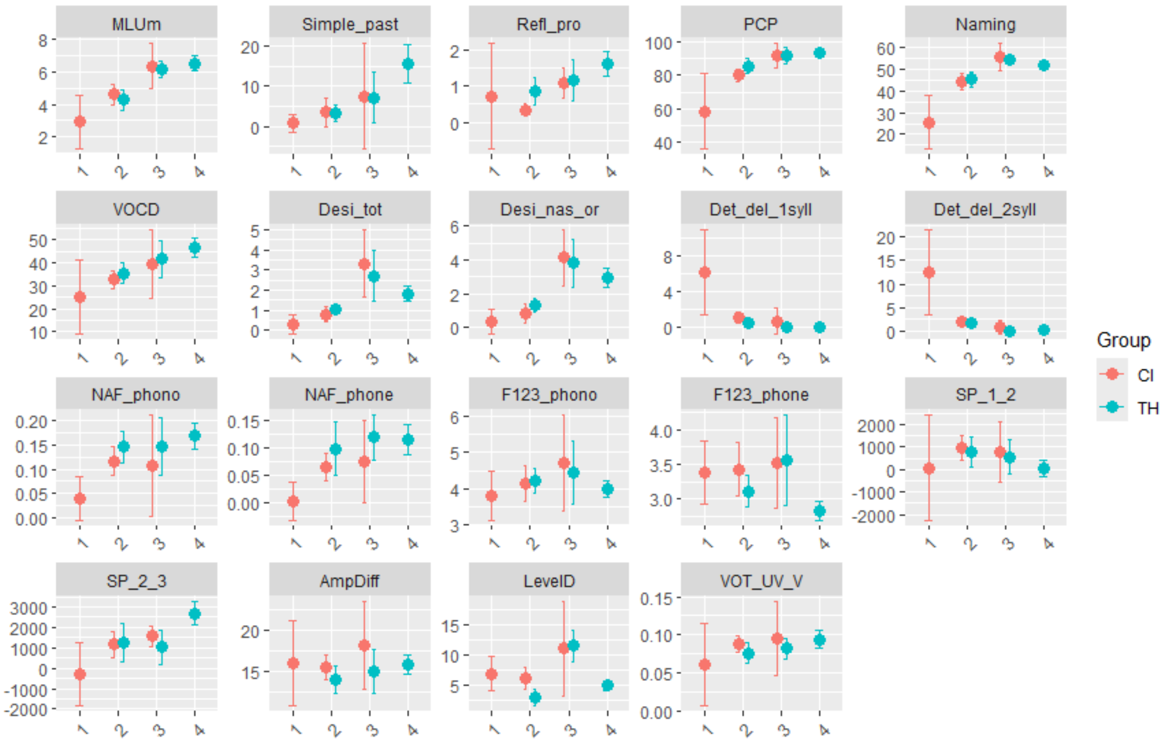

Figure 7.6: Mean values with 95% confidence interval of initial PCA variables, grouped by clusters (X-axis) and differentiated by auditory status (color).

Cluster 2: The children in cluster 2, composed of the same proportion of children from the CI and TH groups, showed higher values than those of cluster 1 across various linguistic variables: MLUm, PCP and number of correct elicitations, but lower than those of clusters 3 and 4, and also lower than cluster 4 for *D* values. On the acoustic level, they showed higher marking values for distinguishing nasal-oral vowels than cluster 1 for NAF values (for both phonological and phonetic pairs), and higher values than cluster 4 in the distinction of "phonetic" pairs by Euclidean distances in the formant space. The children in this cluster showed better marking of the medial and posterior places of articulation of fricatives than cluster 1 but poorer than group 4, while the levelD values in this group were equivalent to those of clusters 1 and 4. This cluster did not differ from the others in terms of the distinction between voiced and voiceless plosives.

Cluster 3: This cluster showed higher values compared to clusters 1 and 2 for MLUm, PCP, D values and number of spontaneous naming, and equivalent to cluster 4. On the phonetic level, the group had marking scores by the NAF index equivalent to clusters 2 and 3 for NAF values for phonological and phonetic nasal-oral pairs, but higher than cluster 4 for marking of phonological pairs by the Euclidean distances in the formant space. This cluster marked the distinction between the medial and posterior places of articulation of fricatives less than cluster 4 and has the highest levelD values.

Cluster 4: The children in this cluster generally showed the highest linguistic performances. These were equivalent to those of cluster 3 for different measures but have higher number of uses of the past simple, and reflexive pronouns. On the phonetic level, this cluster exhibited the lower F1-F2-F3 Euclidean distance values on the marking of nasal-oral distinction. However, the distinction between the medial and posterior places of articulation was the highest in this cluster.

The mean difference values between the Euclidean distances on F1-F2-F3 for phonological pairs, spectral peaks of the anterior and medial places of articulation for fricatives, as well as the ampDiff index, were statistically equivalent between all the clusters.

It should be noted that for clusters 2 and 3, which include equivalent proportions of children from the CI and TH groups, tests were conducted to observe the effect of auditory status, cluster, and the interaction between these variables on the different measures. Significantly higher values in the TH group, regardless of the cluster, were observed for PCP values ($\chi^2(1) = 3.5$; $p = .05$), and the score for items involving nasal/oral distinction ($\chi^2(1) = 3.4$; $p = .06$). Acoustically, a group effect favoring the TH group was also observed for NAF values in the marking of nasal/oral distinction for phonological ($\chi^2(1) = 4.39$; $p = .03$) and phonetic ($\chi^2(1) = 3.42$; $p = .05$) pairs. Higher values for the ampDiff ratio ($\chi^2(1) = 4.44$; $p = .03$) and levelD ($\chi^2(1) = 3.41$; $p = .05$) were also noted in the CI group.

3.2. Results at T2

A subgroup of 13 children with cochlear implants, drawn from the total study sample, repeated all the experimental tasks a second time (T2), one year after the first (T1). The characteristics of these 13 children are detailed in Table 7.1 (section 2.1).

3.2.1. T1-T2 performance comparisons

Figure 7.7 illustrates the average values obtained by the CI subgroup of children during the two assessments.

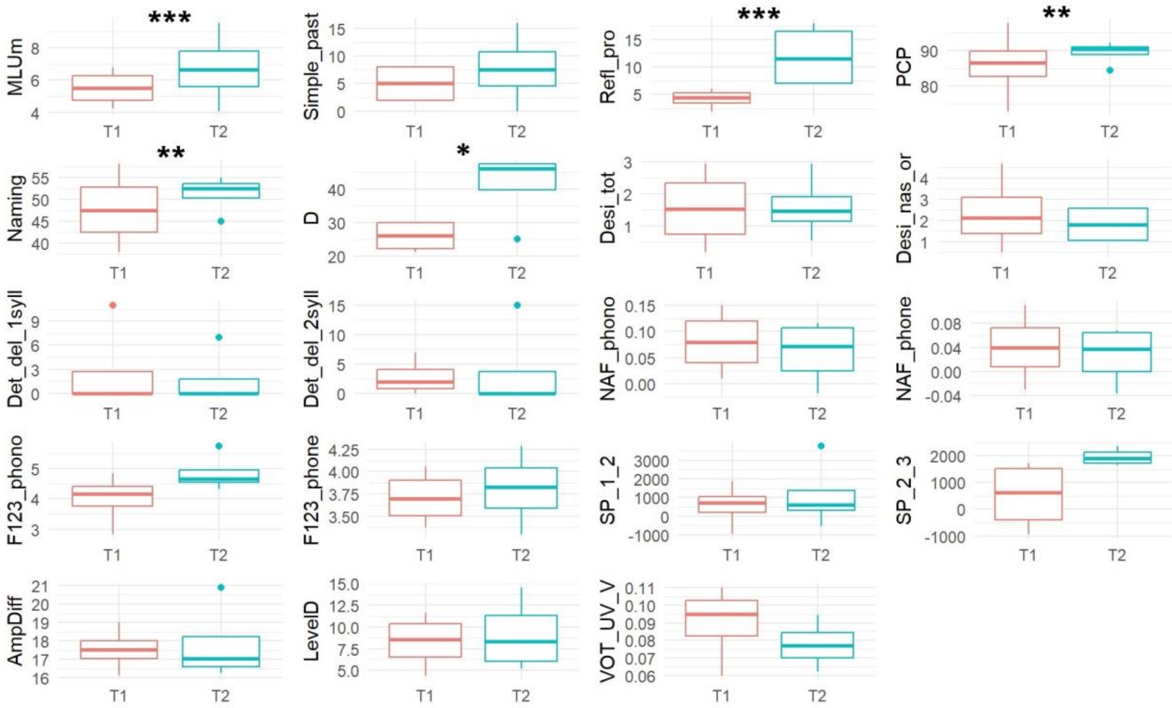

Figure 7.7: Boxplot of the values for the different variables of interest for the CI subgroup at T1 and T2. Significant differences between T1 and T2 are indicated with * (p<.05), ** (p<.005) or * (p<.001).**

Repeated measures analyses demonstrated that performance evolved significantly in the linguistic domain: the values increase for MLUm ($\beta = 1.26$; SE = 0.25; $t(12) = 5.04$; $p < .001$), the number of reflexive pronoun usages ($\beta = 4.5$; SE = 1.15; $t(12) = 3.95$; $p = .001$), the percentage of correct phonemes ($\beta = 5$; SE = 1.4; $t(12) = 2.55$; $p = .003$), the number of spontaneous namings ($\beta = 7$; SE = 2.02; $t(12) = 3.46$; $p = .004$), and the lexical diversity index D ($\beta = 11.4$; SE = 7.07; $t(12) = 2.81$; $p = .01$). Regarding the acoustic variables, changes were observed in relation to fricative consonants: there was an improvement in the distinction between medial and posterior places of articulation ($\beta = 1203$; SE = 276; $t(12) = 4.36$; $p < .001$), as well as an increase in ampDiff values ($\beta = 1.57$; SE = 0.75; $t(12) = 2.1$; $p = .05$). Note that for most measures, the variability of performance decreased at T2.

3.2.2. Factorial analysis and hierarchical classification

The data of the children in the subgroup were projected onto the initial factorial plane by predicting the coordinates on the previously obtained dimensions.

This allowed us to position the children in the subgroup across the different dimensions and to compare their positions between T1 and T2. Figure 7.8 illustrates the differences in positioning between the two assessments on PCA dimensions 1/2 and 2/3.

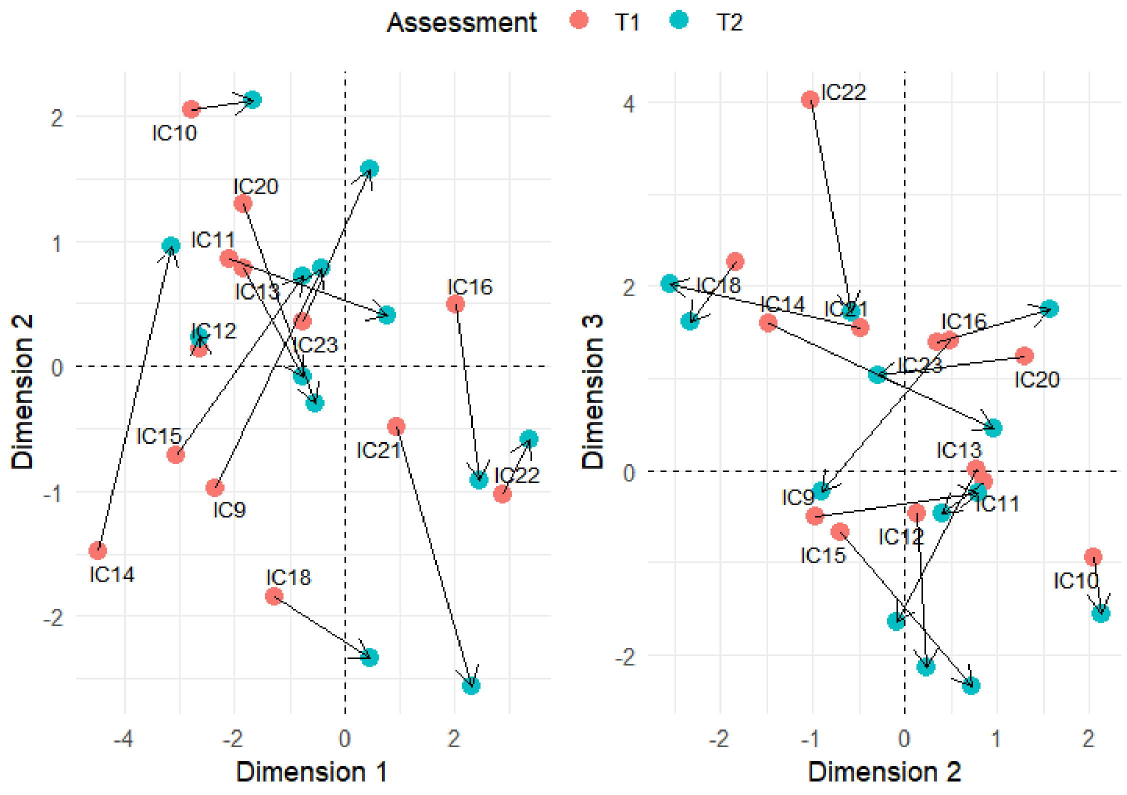

Figure 7.8: Individual plot of children at T1 and T2 on dimensions 1 and 2 (left) and dimensions 2 and 3 (right). The arrows connect the coordinates between the two assessments.

Observation of the shifts along Dimension 1 showed, to varying degrees depending on the participants, a movement towards the positive values of the axis, indicating an improvement in linguistic performance. On Dimension 2, the trends of movement towards positive (N=7) or negative values (N=6) were divided among the subjects. On Dimension 3, however, there was a more general trend towards negative values (N=10), which could signify a better exploitation of nasal resonance cues in the distinction between nasal and oral vowels, and/or a more adequate phonetic realization of fricatives (better distinction of places of articulation; better frication noise). It should be noted that some participants, such as IC10 and IC12, exhibited only very slight shifts between T1 and T2.

Based on the coordinates of the performances in T2 projected onto the initial factorial plane, it was possible to locate the T2 children's performances within the previously formed clusters. Table 7.4 provides information on the assignment of the subgroup of subjects to clusters for the performances in T1 and T2, while also providing the chronological and auditory ages of these children at both assessments.

Subjects	CA - T1	HA - T1	Cluster - T1	CA - T2	HA - T2	Cluster - T2
IC9	57	44	2	69	56	2
IC10	54	42	2	66	54	2
IC11	54	36	2	66	48	2
IC12	66	42	2	71	57	2
IC13	87	61	2	99	73	2
IC14	94	71	1	106	83	**2**
IC15	83	63	2	95	75	2
IC16	81	61	3	96	76	**4**
IC18	45	33	2	60	48	**3**
IC20	44	33	2	58	47	2
IC21	59	42	3	74	57	3
IC22	79	66	3	61	48	3
IC23	60	39	2	75	54	**3**
Mean	66,4	48,7		76,6	59,7	

Table 7.4: Chronological (CA) and auditory ages (AA), along with cluster assignments at Testing 1 and Testing 2, for the CI subgroup of children.

It can be observed that only four children changed clusters: IC16 moved from Cluster 1 to Cluster 2, IC20 and IC25 moved from Cluster 2 to Cluster 3, and IC18 moved from Cluster 3 to Cluster 4. The other children remained in the same clusters as in T1.

Figure 7.9 represents the performances on the different variables of interest during T1 and T2, focusing on the four participants who changed clusters.

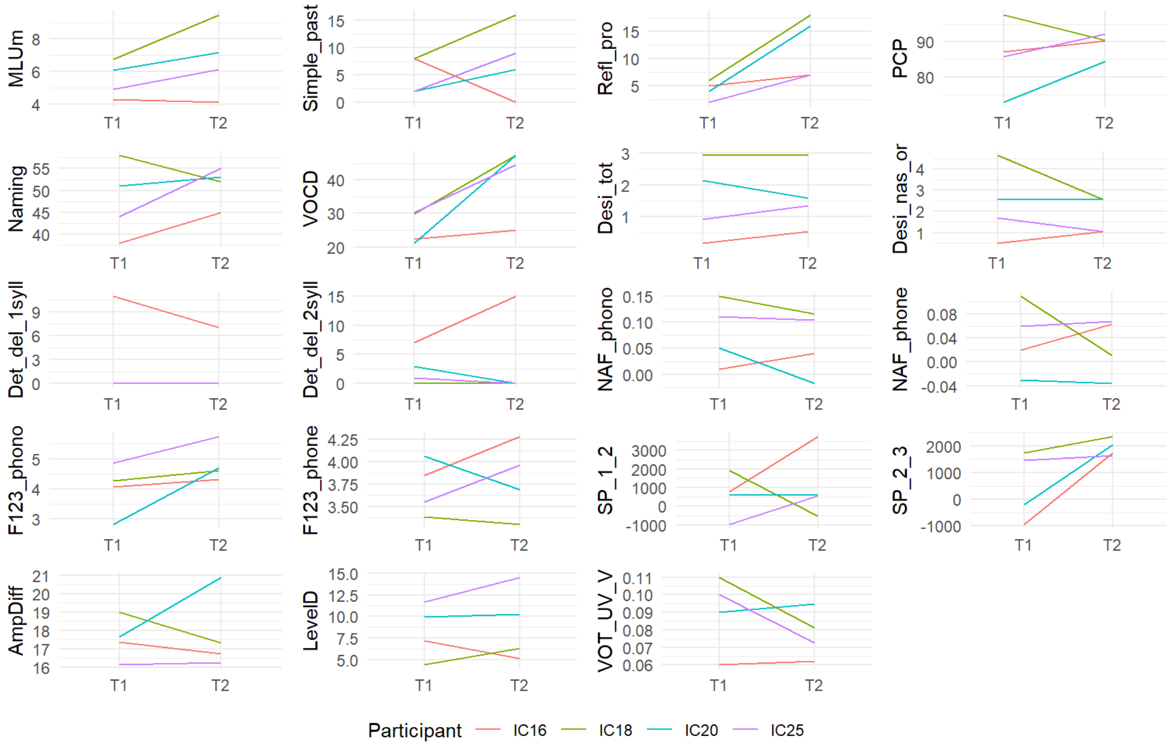

Figure 7.9: Performance of the 4 children who changed clusters between T1 and T2 across the different variables of interest.

For subject IC16, who joined Cluster 2 at T2, the changes were mainly observed in terms of an increase in the percentage of correct phonemes and spontaneous naming, a decrease in determinant omissions in front of monosyllabic words (with an increase in front of bisyllabic words), an increase in the marking of nasal-oral distinctions in terms of oropharyngeal configuration, as well as better distinction between the places of articulation of fricatives. The improvements for the other subjects were more related to the overall linguistic scores, with increases in MLUm values, use of the imperfect tense and personal pronouns in narratives, as well as in lexical diversity. Subject IC20 also showed better marking through oropharyngeal configuration in the production of nasal/oral vowels, better distinction of fricative places of articulation, and higher ampDiff values.

4. Discussion

The aim of this study was to jointly examine the production profiles of children with CI and children with TH on three segments which acoustic correlates pose different challenges to the implant (nasal/oral vowels, fricative, and plosive consonants), in relation to their phonological, lexical, and morphosyntactic linguistic skills. To do this, factor analyses were conducted, leading to the creation of clusters via hierarchical clustering. Various influencing factors were considered, such as chronological/auditory age, parents' socioeconomic status, exposure to sign language (SL), and the age at which the implant was received. A subgroup of children with CI also completed the tasks a second time, one year after the first data collection session, allowing for a comparison of their performance over time, from a longitudinal perspective.

The factor analysis revealed three dimensions explaining approximately 50% of the total variance. The first dimension was directly related to all linguistic performance: phonological scores, the number of spontaneous namings in the picture-naming task, lexical diversity scores, sentence/word-picture matching scores, as well as scores related to morphosyntactic development. This dimension clearly distinguished the children according to their auditory status, with children in the CI group generally exhibiting weaker linguistic performances. The association of various linguistic competencies—phonological, lexical, and morphosyntactic—seems to show a relatively homogeneous joint development of these performances within our sample. This might seem to contradict some literature suggesting a special status of lexical competencies compared to other linguistic skills, which could be more preserved due to the greater perceptual and conceptual salience of lexical elements in language representations (Caselli et al., 2012; Duchesne et al., 2009; Le Normand & Moreno-Torres, 2014; Rinaldi et al., 2013). However, this finding has not always been confirmed, other studies such as (Cambra et al., 2021; Fagniart et al., 2024b; Le Normand & Moreno-Torres, 2014) highlighting an increased vulnerability of children with CI also in lexical skills.

PCA Dimensions 2 and 3 were related to acoustically defined speech production profiles: while high performance on axis 2 demonstrated the ability to distinguish nasal-oral contrasts regardless of the production strategy (oral vs. oro-nasal resonance; adoption of a specific oropharyngeal configuration), dimension 3 differentiated between the two production strategies to implement the nasal-oral distinction. On this dimension, the groups of children were again well distinguished: children in the CI group were more positioned toward the positive values, indicating a greater tendency to mark the nasal-oral distinction through distinct oropharyngeal configurations, as opposed to the TH children, who more often employed oral vs. nasal resonance. This finding was not unexpected since it corroborates observations made on speech productions obtained through the repetition of pseudowords containing nasal and oral vowels (Fagniart et al., in press). It should be noted that dimension 3 was also associated with the quality of fricative production (levelD values) and the distinction between medial and posterior places of articulation for fricative consonants, with children in the CI group being associated with lower quality (higher levelD values) and less distinct productions.

The hierarchical classifications based on the dimensions of the factor analysis allowed for the division of the sample of children into four clusters. These clusters were very distinct on Dimension 1, which relates to linguistic performance, and on Dimension 3, which relates to nasal-oral vowel distinction through nasal resonance vs. oropharyngeal configuration. Two highly contrasting profiles emerged from the cluster formation through hierarchical classification, which particularly drew our attention. While Cluster 4, composed solely of children from the TH group, exhibited the highest linguistic performance, the children in Cluster 1, composed entirely of children with cochlear implants (CI), displayed the lowest linguistic performance. These differences did not seem to be related to age: although the children in Cluster 1 had a lower auditory age compared to the children in Cluster 4, their average auditory age was equivalent to that of the CI children in Clusters 2 and 3, and even to the TH children in Cluster 2, yet they did not reach the same performance levels. These children, whose performance remained significantly below that of peers with the same auditory age, might represent the atypical developmental profiles suggested by some authors (Benassi et al., 2021; Majorano et al., 2024) and/or contribute to the variability in performance that is generally present and somewhat difficult to explain as noted in the literature. Clusters 1 and 4 were also very distinct on their speech production profiles. Children in Cluster 4 marked the nasal/oral vowels distinction using typical production mechanisms (oral vs. oro-nasal resonance, specific oral configuration), clearly distinguished between the places of articulation of fricatives with frication noise involving mid and high-frequency ranges, and clearly contrasted voiced and unvoiced plosives in terms of VOT. In contrast, children of Cluster 1 showed little marking of the nasal/oral distinction using cues reflecting the presence or absence of nasal resonance, with no compensation by increased marking in terms of oropharyngeal configuration. The places of articulation of fricative segments, marked by high-frequency cepstral peaks, were poorly distinguished, with frication noise primarily involving mid frequencies only. Voiced/unvoiced plosives were also less distinguished in terms of VOT. This productive profile seemed to fully reflect the impact of the specific sound transmission limitations of the CI: limitations in the perception of fine spectral details in low frequencies (impacting nasal/oral vowel distinction) and in the perception of high frequencies in general (places of articulation of fricatives – frication noise). However, these children did not seem to compensate for these perceptual difficulties by better exploiting the acoustic cues supposedly better coded by the implant, such as temporal cues (VOT for voicing of plosives) or cues related to oropharyngeal configuration (formant frequencies). These significant and poorly compensated perceptual difficulties, resulting in underspecified phonological representations, are likely to impact overall linguistic abilities, as observed in the children of this group. These findings are consistent with the link between phonological and linguistic development proposed in various models developed in the context of specific language impairments (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992), which apply in this case to the perceptual limitations associated with CI.

Clusters 2 and 3, composed of equivalent proportions of children from the CI and TH groups, present intermediate profiles in terms of linguistic performance. Cluster 2, for instance, showed superior performance compared to Cluster 1 across all linguistic measures, while Cluster 3 differed from Cluster 4 only in the use of more complex grammatical markers (reflexive pronouns, imperfect tense). Acoustically, Cluster 2 and Cluster 3 differed slightly: children of both groups exhibit a relatively balanced marking of the nasal-oral distinction between production strategies based on nasal resonance and oropharyngeal configuration. While both groups equally distinguished the places of articulation of fricatives, children of Cluster 3 have the highest levelD values, indicating a lower concentration of high-frequency ranges in their frication noise. It is noteworthy that an auditory status effect was similarly observed in both clusters: within these groups, CI children have lower nasal resonance marking values compared to TH children, but higher oropharyngeal configuration marking. As to levelD values, they are consistently lower (with less concentration of energy in high frequencies) in the TH children. Therefore, these two subgroups of CI children in Cluster 2 and 3 appear to exhibit speech productions that are influenced by the specific limitations of CI, reducing their ability to exploit cues that are imprecisely coded by the implant (nasal resonance, high-frequency energy), but unlike the children in Cluster 1, they have implemented effective compensatory strategies. Indeed, the marking of the nasal-oral distinction through the overuse of oropharyngeal configuration cues has been reported as having a significant impact on the intelligibility of productions (Fagniart et al., in review). Furthermore, the fact that these children correctly distinguish voiced and unvoiced plosive segments using VOT demonstrates good exploitation of the temporal cues supposed to be more precisely coded by CI. More generally, an effective exploitation of temporal cues by children with CI has been reported to have a positive impact on spectral resolution processing (Landsberger et al., 2019), as well as on their performance in the identification and discrimination of nasal and oral vowels (Fagniart et al., 2024a). These various elements could explain why their linguistic performance was higher compared to Cluster 1.

An attempt was made to investigate whether the participants' characteristics could account for their distribution within the clusters. An effect of chronological age on the distribution between clusters was observed in the TH group: the average age of the children was progressively higher between Clusters 2, 3, and 4, reflecting a gradual development of linguistic skills and mastery of phonetic distinction mechanisms. The speech production profile of the TH children within Cluster 3 was more surprising, since older ones showed a lower representation of high frequencies in frication noise and an emphasis on marking the nasal-oral distinction through oropharyngeal configuration. The presence of such a profile among typically hearing children may illustrate significant inter-individual variability in the development of productive skills in the general population, which, however, did not seem to significantly impact linguistic development, as evidenced by the high linguistic performance of this group. Regarding the children in the CI group, the differences between clusters could not be explained by chronological age or auditory age, as the three clusters had equivalent mean values. However, the gap between the ages of children in the CI and TH groups was not the same between clusters, depending on whether chronological age or auditory age was considered. Indeed, while the children in the CI group were on average older in terms of chronological age than the children in the TH group within Clusters 2 and 3, it was found that children with CI had average auditory ages equivalent to the chronological age of TH children within Cluster 2. The intermediate performance of CI children in this cluster could therefore be explained by delayed exposure to auditory input through the CI and may be related to the literature showing equivalent linguistic performance between TH and CI children when they are matched by auditory ages (Guo & Spencer, 2017). In this sense, the children with CI in Cluster 3 may have represented a more advantageous profile, since their average auditory age was lower than the chronological age of the TH children in the same group whereas they presented equivalent productive mechanisms indicating advanced exploitation of compensatory mechanisms, leading to high linguistic levels.

The different characteristics of all participants as well as specific information related to the CI group (early implantation, exposure to CS) did not reveal any statistic relation with the distribution between clusters. It therefore appears that within our sample, compensatory strategies for perceptual difficulties may (or may not) be implemented independently of multimodal stimulation through CS or linked to an early implantation profile. These results contrast with previous findings in the literature regarding the positive impact of early implantation (Karltorp et al., 2020; Kral et al., 2019; Sharma et al., 2020; Tamati et al., 2022) or CS exposure (Bouton et al., 2011; Leybaert et al., 2016; Leybaert & LaSasso, 2010; Machart et al., 2024; Van Bogaert et al., 2023). However, it is possible that the present analyses, which encompass both acoustic production performance and various linguistic measures, capture a greater amount of inter-individual variability than studies focusing on a single aspect of language or speech. The combination of all these aspects of language studied together reveals profiles that did not clearly identify favorable or unfavorable factors. It is noteworthy that a previous study, specifically evaluating morphosyntactic skills in a subgroup of the children from the present study, found equivalent performances between children who were not exposed to CI and those who were exposed early and consistently (study 5 – chapter 6). This suggests that among some of the non-exposed to CS and later implanted children, uncontrolled favorable factors within the study and/or natural variability allowed them to achieve high linguistic competence. It is conceivable that favorable environmental conditions, such as strong parental involvement, appropriate follow-ups, and adequate oral language stimulation, may have led to better linguistic performances.

Although the statistical analyses did not reveal any significant links between individual variables and the cluster distribution, a qualitative analysis of the characteristics of the children in the cluster with low linguistic performance and imprecise acoustic production profile in Cluster 1 highlights certain conditions that may be considered unfavorable for the linguistic development of children with CIs. Firstly, 3 out of the 5 children received their first implant after the age of two, which could represent an unfavorable condition for speech development given the demonstrated importance of early implantation (Karltorp et al., 2020; Kral et al., 2019; Sharma et al., 2020; Tamati et al., 2022). Moreover, among 4 of the 5 children in this cluster, the socio-economic status (SES) of the parents was low. Although SES, as evaluated by the average level of parental education, has shown mixed results in the literature (Holzinger et al., 2020), some authors have observed links with linguistic development and suggested that wealthier families may have greater access to information and a better understanding of the mechanisms related to deafness which is a prerequisite to an adequate child support (Moreno-Torres et al., 2016). Access to these resources could be related to the quality of interactions and the level of oral stimulation in the family context, and perhaps also to the family's level of involvement, all of which can contribute to language development. On the contrary, less affluent families might find themselves more deprived and have fewer resources to implement appropriate support for their child's language development. As these aspects (family involvement, quality and quantity of oral stimulation) were not evaluated in the present study, these assumptions remain hypothetical and would require further investigation in future studies. Moreover, it should be noted that among these children of Cluster 1, 2 are not exposed to Cued Speech (CS), while 2 others have only occasional exposure, and only 1 child has regular and early exposure. The positive impact of exposure to CS has been demonstrated in numerous studies involving children with cochlear implants (Bouton et al., 2011; Leybaert et al., 2016; Machart et al., 2024; Van Bogaert et al., 2023), as the visualization of language contrasts through the manual cues of CS can help compensate for their perceptual difficulties. However, the exposure needs to be early, regular, and highly sustained to constitute a favorable condition for development (Charlier, 2020). In Chapter 6, it was observed that the CS- group, exposed only occasionally to CS, achieved the lowest performances in grammatical production. Although, again, no statistical effect could establish a link between CS exposure and the distribution among clusters, Cluster 1 mostly comprises children who do not present favorable conditions for exposure to this method, which has shown beneficial effects on speech and language development. Finally, it should also be noted that one child is raised in a bilingual environment (this element will be discussed later), and another child in the cluster is only unilaterally implanted. Bilateral implantation has been shown to facilitate sound localization and speech perception in noise (Dunn et al., 2010; Müller et al., 2002), and it also appears to be favorable for better perception of speech sounds through what is termed ‘‘perceptual redundancy’’ of spectral information across both cochlear implants (Sarant et al., 2014). A positive effect of bilaterality has been suggested, given the higher results obtained in the identification and discrimination of nasal and oral vowels among children with bilateral cochlear implants (Fagniart et al., 2024a) compared to a study that tested children with unilateral cochlear implants (Bouton et al., 2012). It is possible that participant IC6, despite a high socioeconomic status and early implantation, may have been disadvantaged by a unilateral implantation in the evaluated performances.

The comparison of the performance of the subgroup of children with cochlear implants (CIs) who were tested one year apart revealed a group trend towards improved linguistic skills (MLU, use of reflexive pronouns, percentage of correct phonemes, naming, lexical diversity) as well as improvements in the quality of fricative consonant production, with better distinction between medial and posterior places of articulation and increased representation of mid-range frequencies in frication noise (higher ampDiff values). These changes may explain the shifts in these children along the dimensions of the factor analysis after projecting their new data onto the initial model: a movement towards positive values on dimension 1 (better linguistic skills) and negative values on dimension 3 that seemed related to improvements in the quality of fricative production—the indices related to nasal vowels did not change. The fact that the children in this subgroup generally improved in distinguishing fricative places of articulation acoustically but not in mastering aspects related to the nasal resonance of vowels is interesting when linked to the spectral and articulatory characteristics of these segments. As explained in detail in Chapter 2, the processing of spectral resolution, necessary for distinguishing the nasal or oral nature of a vowel, primarily depends on the fine spectral processing of low-frequency information. However, low frequencies are more likely to be imprecisely encoded through the CI, with various sources of variability related to the depth of electrode insertion and different etiological, anatomical, and surgical conditions. This variability likely explains the initial varying levels of mastery in distinguishing nasal-oral vowels using nasal resonance in production, without leading to clear improvements over time. In contrast, for fricative consonants, perceptual limitations related to processing high-frequency information could be compensated for through linguistic experience by mastering somatosensory correlates and visually perceiving different places of articulation.

Indeed, the different places of articulation for fricatives lead to labial differences that are visually accessible. The more effective development of multimodal speech perception through maturation and linguistic experience could have led to greater mastery of this distinction in production, despite the associated perceptual limitations. The fact that only the ampDiff values, related to the presence of mid-range frequencies in the frication noise, and not the levelD values, related to the presence of very high frequencies, show improvement, is further evidence for the persistence of these perceptual limitations in high frequencies.

The hierarchical clustering of the new data resulted in few changes in cluster distribution, with only 4 out of the 13 children changing clusters. It is encouraging to observe that one of the children included in the most disadvantaged cluster, Cluster 1, has moved to one of the intermediate performance clusters, Cluster 2. Notably, this child is among the oldest, both in terms of auditory and chronological age, and comes from a bilingual family environment. Family bilingualism is suggested as a risk factor in the linguistic development of deaf children, necessitating additional close monitoring (Vukkadala et al., 2018). This observation has been made in other studies that highlight the significant impact of factors potentially associated with bilingualism, such as socio-economic status and/or parental involvement (Deriaz et al., 2014). In children with CIs, these findings are more nuanced, with some studies reporting lower performance among bilingual children (Deriaz et al., 2014) but sometimes equivalent performance compared to monolingual children (Sosa & Bunta, 2019; van der Straten Waillet et al., 2023). Again, the authors emphasize the importance of the family environment, parental involvement, and the level of oral stimulation the child receives in both languages. It is worth noting that this child also presented two additional risk factors, namely a low average level of parental education and a first implantation after the age of 18 months. These factors, combined with family bilingualism, may have contributed to a developmental profile significantly delayed compared to peers. However, the transition to Cluster 2 indicates that the child's developmental profile does not appear to be atypical and can positively evolve through maturation and experience. Concerning the three other children who changed clusters, it is worth noting various factors that could be considered favorable: these three children had an implantation age of under two years, and two of them benefited from early and sustained exposure to Cued Speech (CS). Participant IC16 even achieved performances that allowed them to access Cluster 4, which initially only consisted of children with typical hearing and the highest linguistic performances.

It is also noteworthy that this participant comes from a high socioeconomic status (SES) family, which could be an additional favorable factor. However, among all the participants who completed the second testing, the majority of the children (9 out of 13) remained in the same cluster, indicating a progression in performance that did not allow them to catch up with the superior linguistic performances of Clusters 3 and 4, despite their advancement in chronological and auditory age. This subgroup of children, therefore, remains within Cluster 2 and now shows a discrepancy between their average auditory age and the average chronological age of the typically hearing children assigned to this cluster in the initial model. This result could support findings in the literature from longitudinal studies showing a slower rate of acquisition in groups of children with cochlear implants (Chilosi et al., 2013; Moreno-Torres et al., 2016). This slower rate of acquisition could be explained by the need for adequate use of the compensatory strategies previously described at the perceptual-productive level. These strategies may require more cognitive resources and result in language development that aligns with that of typically hearing children with a lower chronological and auditory age.

Although this study provides numerous perspectives for future investigations, it has several limitations that should be considered. Firstly, the small number of participants and the difficulties in balancing the sample in terms of chronological/auditory ages, age of implantation, exposure to CS, etc., require a cautious interpretation of the findings. Furthermore, the longitudinal approach was only partial: only a portion of the subgroup of CI children could be recruited for the second session of data collection, which did not allow for an examination of the progression of the overall performances and the entirety of each cluster, thus limiting interpretations of potential influencing factors. It would have also been beneficial to have more data points and a longitudinal perspective for children with typical hearing as well. The age effects in this group should be observed cautiously, as they were studied based on samples of different age groups.

5. Conclusion

The overall study of performance in the phonological, lexical, and morphosyntactic domains, as well as the speech production profiles based on the acoustic analyses of a variety of phonetic segments, has highlighted various profiles among a group of children with cochlear implants (CI) compared to their typically hearing peers:

- A group of children with difficulties across all investigated linguistic skills, combined with speech production profiles suggesting significant and poorly compensated perceptual difficulties. These profiles, although interpreted cautiously given the small sample size, may be associated with late implantation ages, low socioeconomic status (SES), and lack of or limited sustained exposure to Cued Speech (CS).
- Two groups of children with linguistic performances equivalent to those of typically hearing children of the same auditory ages, with speech production profiles showing the use of compensatory strategies for perceptual difficulties related to CI.
- A progression in performance over a one-year interval for only 4 out of 13 children with CI, indicating a difficulty in developing skills at a rate equivalent to that of typically hearing children.

Chapter 8 General discussion

The objective of this general discussion is to synthesize the main findings that provide elements of an answer to our primary research question, which investigates the links between perceptual limitations and grammatical development. This will be followed by a more precise discussion of the different potential sources of variability that have been studied. Next, we will reflect on the issues related to sensitive periods in language development and concluding with a proposed model of potential sources of variation in the language performance of children with CI, as well as the clinical perspectives arising from the various findings and the limitations of the studies conducted.

1. Perceptual limitations

Before addressing the links between the perceptual limitations of cochlear implants (CI) and linguistic components, we will focus on the studies that have investigated these limitations through a perceptual study and three production-focused studies, emphasizing the particularly effective adaptation and compensation abilities observed in certain groups of children.

1.1. A constrained but adaptative and compensatory perceptual system

The first study (*Perception of the vowel nasality feature* - Chapter 2) investigated perceptual skills through identification and discrimination tasks involving pseudowords containing nasal vowels as well as oral vowels that are close phonologically or phonetically, according to the classification proposed by Borel (2015). The CI children's performance was significantly lower than that of the typically hearing (TH) children in the identification task, and more difficulties were observed in the discrimination of phonetic pairs (Fagniart et al., 2024a). These difficulties support the hypothesis of an increased challenge in perceiving the acoustic correlates related to nasal resonance, which are carried by fine acoustic cues and require optimal spectral resolution skills especially in the low-frequency range. However, the performance was much higher than that observed in studies involving adults (Borel, 2015; Borel et al., 2019) and unilaterally implanted children (Bouton et al., 2012). We suggested that the perceptual system of children born deaf and implanted early could be better adapted to the degraded CI signal compared to post-lingually deaf adults (Landsberger et al., 2019), and that there might also be a beneficial effect of “binaural redundancy” (Sarant et al., 2014) due to the use of bilateral implants in processing fine spectral signals, which could have advantaged the children in the sample. The level of Cued Speech (CS) exposure also showed effects, with children who had early and sustained exposure (CS+) achieving better scores than those with occasional exposure. Furthermore, the performance of these CS+ children was positively correlated with the prevalence of temporal cues among the stimulus characteristics. This suggests that exposure to CS, by making phonological contrasts visually explicit, may promote the use of salient cues that are both well-coded by the CI and relevant for discriminating between French oral and nasal vowels, hence the better performance of CS+ children.

These different propositions were supported by the results of the second study (*Production of oral and nasal vowels* - see chapter 3), which focused on the same children’s productive skills in distinguishing between French nasal and oral vowels. Perceptual judgments revealed that the oral and nasal vowels produced by CS+ children were best identified, since they achieved slightly higher scores than the TH children and significantly higher than the CS- children (Fagniart et al., in press). The CS- children had their nasal vowel productions judged as less nasalized on perceptual scales and had more “intermediate” productions (neither judged very oral nor very nasal). Acoustic analyses showed that the distinction between nasal and oral vowels was more often based on vowel length and cues related to the oropharyngeal configuration (formant frequencies) in CI children, particularly CS+ children, compared to TH children. Conversely, NAF measures, which reflect the degree of nasal resonance, were significantly lower among CI children. These data once again reflected, on the one hand, the limitations inherent in the CI’s coding of the sound signal affecting the children’s ability to process (Borel, 2015; Borel et al., 2019; Bouton et al., 2012; DiNino & Arenberg, 2018; Henry et al., 2005; Horn et al., 2017) and therefore to produce phonetic cues related to nasal resonance, and on the other hand, the possibility of compensating for these difficulties by using perceptually advantageous cues. Vowel duration and formant frequencies are likely to be better encoded by the implant, with the latter being associated with visually accessible configurations (at least when they involve articulatory movements such as lip rounding or jaw opening). This production profile was more frequently found among the most intelligible children, the CS+ children, and was also associated with the productions that were best discriminated in terms of nasality by the judges.

The studies exploring the production of fricative segments (Chapters 4 - *Production of fricative consonants* - and 5 - *Consonant and vowel production: an integrative study*) also supported the findings in the literature regarding the increased vulnerability of these segments, which perception rely primarily on acoustic information in the high-frequency ranges that approach the limits of CI coding (Loizou, 2006; Reidy et al., 2017). The perceptual limitations related to these segments were evident, on the one hand, in generally lower spectral peak values and less distinct places of articulation among fricatives (Giezen et al., 2010; Hedrick et al., 2011; Lane et al., 2001; Mildner & Liker, 2008; Reidy et al., 2017), and on the other hand, in a distribution of fricative noise energy that was more concentrated in the low and mid frequencies, which is associated with a weaker constriction force (Fagniart et al., 2024c, 2024b). These production patterns may explain the deficits observed when phonological accuracy was measured, which revealed more atypical errors such as fricativization and voicing errors (Fagniart et al., 2024c). Unlike nasal and oral vowels, fricative segments seem to benefit less from acoustic correlates that could compensate for the challenges in processing high frequencies with CI, since less beneficial impact from CS exposure is observed for fricatives (Chapter 4 and 5). However, it should be noted that in the last study (*Phonetic, phonological, morphologic, lexical and morphosyntactic skills : an integrative study* - Chapter 7), the productive performances, as evaluated using a picture-naming task, showed a marked improvement in the ability to distinguish between fricatives after a one-year interval. It is possible that with more linguistic experience, the children were better able to use the visual cues related to the places of articulation of these segments and/or to improve their productive skills through proprioceptive feedback associated with different places of articulation. However, this improvement was not observed in the levelD values. LevelD values reflect the use of high frequencies in fricative noise; the fact that these values do not change indicates clear limitations of the perceptual system that cannot be compensated for by exploiting accessible cues - as no visual cues are available to perceive this production mechanism.

Concerning the voicing feature of plosives, as studied through voice onset time (VOT), a strictly temporal measure, the results were consistent with those in the literature (Grandon et al., 2017; Horga & Liker, 2006; Uchanski & Geers, 2003), showing shorter positive VOTs for voiceless plosives but longer negative VOTs for voiced plosives during a naming task. However, it is noteworthy that for the items requiring repetition of the target word by the experimenter, the children's productions aligned with those of typically hearing children regarding positive VOTs, indicating a potential to adequately use the temporal cue related to the distinction.

The studies summarized so far collectively allow us to assert that the perceptual system of prelingually deaf children is able to adapt and compensate for perceptual limitations using other, relevant acoustic cues at their disposal, in order to adequately process the phonological contrasts present in the phonological systems of their native language. These compensatory mechanisms depend on the set of acoustic correlates associated with phonological contrasts, as evidenced by the more challenging difficulties to compensate for in fricative segments. As they are also variably observed among the children, the impact of activating multimodal speech perception through CS is particularly interesting to consider.

1.2. Multimodality of speech perception

In these first studies that were carried out as part of our research on the perceptual and productive profiles in the document, a positive impact of exposure to CS was observed on the use of relevant acoustic cues and, consequently, on the compensatory mechanisms in the perceptual system. This was particularly noted both in the perception and production of the distinction between nasal and oral vowels within pseudowords, as well as in frequent words during a picture-naming task. We hypothesize that this advantage is directly related to better integration of visual cues through lip-reading, combined with an internalized representation of the manual cues of CS. The visualization of phonological contrasts enabled by CS promoted attention to the relevant cues for discriminating the phonological contrasts of the language - in the case of vowel nasality, through the use of temporal and visual cues. This effect was also observed in the distinction of the places of articulation of fricative consonants, whose acoustic correlates are less available due to their representation in high-frequency ranges but whose articulatory characteristics may be partially accessible visually.

These data support findings in the literature that demonstrate a benefit in language development for children with cochlear implants, both in terms of perception and production (Bouton et al., 2011; Leybaert et al., 2016; Leybaert & LaSasso, 2010; Machart et al., 2024; Van Bogaert et al., 2023). Children exposed to Cued Speech early and intensively seem to develop more stable phonological representations that incorporate information from manual cues, as evidenced by studies on multimodal speech perception that combine auditory information, lip reading, and manual cues (Bayard et al., 2014). The observation in Chapter 2 of auditory confusions between vowels coded at the same place (/u/ - /ɛ/) is consistent with these findings.

Leybaert & LaSasso (2010) identified five main reasons why exposure to Cued Speech (CS) for children with cochlear implants (CIs) can provide optimal conditions for language learning. First, the most obvious reason is that CS, through its visual contribution to speech perception, facilitates the acquisition of the phonological contrasts of the language. The perceptual limitations associated with the CI, which cannot be disambiguated through lip reading, are compensated by the visualization provided by the CS system, thus enabling the formation of a complete phonological system. Second, exposure to CS draws attention to lip-reading and provides effective training in this skill, which has been demonstrated experimentally (Colin et al., 2008). Third, CS facilitates the natural development of language. Indeed, it has been observed that cochlear implantation can lead to an overconfidence on strictly auditory abilities, both in the child and in their surroundings, potentially resulting in the overuse of compensatory mental strategies (top-down processes) and, consequently, in underdeveloped auditory representations. In this sense, exposure to CS can help avoid this pitfall by making the sub-lexical elements of language fully accessible, as evidenced by better results in segmental perception (Fagniart et al., 2024a; Van Bogaert et al., 2023) and production (Fagniart et al., 2024ba; Fagniart et al., in press; Machart et al., 2024), as well as in morphosyntactic development (Hawes, 2004; Leybaert & LaSasso, 2010, results of studies 5 and 6). Furthermore, for individuals who received an implant later in life, the benefits of cochlear implantation are greater if they were previously exposed to CS (Archbold et al., 2008; Kos et al., 2009). This exposure may help prepare the auditory system to receive input of the same syllabic and sequential rhythmic nature, further supporting the benefits of this method. Finally, this method has been recognized for improving speech intelligibility in noisy environments (Leybaert & LaSasso, 2010), which are common in learning contexts or peer interactions. These various elements may contribute to the better language performances observed among children with early and intensive exposure to CS. However, it should be noted that early and intensive exposure seems to be necessary conditions to derive significant benefits for language, as evidenced by the lower performances as well as the acoustic production profiles within the linguistic components of children with occasional exposure (CS- group).

2. Phonological, lexical and morphosyntactic development

After this thorough investigation of the perceptual-productive profiles of children with cochlear implants (CI) compared to their typically hearing peers, we also examined in Chapters 6 and 7 the phonological, lexical, and morphosyntactic components of their developing linguistic abilities. As a group, children with CIs showed significantly lower performance across all the linguistic components investigated. This was evidenced by lower scores in phonological accuracy for the different segments studied, weaker lexical performance as evidenced by fewer spontaneous naming responses in a picture-naming task, and less lexical diversity in narrative tasks. In terms of grammatical skills, children with CIs showed shorter mean utterance lengths in terms of morphemes (MLUm), fewer utterances containing a verb, poorer verbal morphology, fewer complex function words and more morphological errors than their typically hearing peers.

2.1. Relationship between phonology and morphosyntax

To investigate the hypothesis that there is a perceptual/phonological origin for the increased difficulties in the morphosyntactic domain, grammatical skills were linked, on the one hand, with phonological skills and, on the other hand, with lexical scores. This was done to distinguish between connections due to a general maturation effect of the linguistic system and those specifically related to the phonological system. The results from Chapter 6 highlighted a special link between phonological accuracy and grammatical development in children in the CI group, whereas children in the TH group showed more equal contributions from phonological and lexical stages to their grammatical performance. This suggests that grammatical development in children with CIs is more dependent on phonological skills, which in turn depend on the limitations imposed on the perceptual system and its capacity for adaptation/compensation. Furthermore, we found specific difficulties in morphemic processing in children with CI, in this case in discriminating items whose morphophonological opposition is based on distinctions between nasal and oral vowels. This indicates that the difficulties in grammatical processing were not generalized but were specifically related to with the perceptual challenges characteristic of children with CIs.

This specific link between phonological and morphosyntactic skills is entirely consistent with the phonological theories of MS development in developmental language disorders (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992), which state that perceptual limitations affect the perception and production of morphemes, particularly regarding grammatical morphemes which are more vulnerable due to their lower perceptual and conceptual salience. However, this can also be associated with various studies that have demonstrated specific difficulties in verbal working memory in children with cochlear implants (CI) compared to other cognitive functions (Nicastri et al., 2024). Two main hypotheses have been proposed to explain the verbal working memory difficulties in children with cochlear implants (CI): the auditory scaffolding theory and the phonological bottleneck hypothesis. According to the first, hearing is inherently designed for processing information of a temporal and sequential nature, which develops from the very first auditory experiences (Conway & Christiansen, 2005). Thus, any delay in exposure to these auditory experiences will delay the acquisition of these sequential processing functions, directly impacting linguistic skills that rely specifically on sequential patterns. The primary source of this delay is the period of auditory deprivation itself. This hypothesis is supported by various authors who position the linguistic difficulties of CI children within the cognitive domain rather than purely the sensory one (Conway et al., 2009, 2014; Kronenberger et al., 2014; Pisoni et al., 2016). The second main hypothesis, the phonological bottleneck hypothesis, based on previous studies in dyslexia (Bar-Shalom et al., 1993), suggests that the difficulties in verbal memory are mainly caused by poor phonological awareness. This hypothesis is based on the observation of particularly high phonological difficulties compared to other linguistic components, explained by degraded auditory representations due to the processing limitations of the CI. These degradations, mainly affecting spectral structures, are suggested to “curtail” the children’s ability to adequately use phonological representations to store verbal material within short-term verbal memory. According to this hypothesis, the origin of the difficulties is sensory, resulting from the degradation of the auditory signal by the CI.

Nittrouer et al. (2017) specifically confronted these two hypotheses in a study evaluating serial recall skills in 46 children with CIs and 47 children with typical hearing. Various predictors of the measures obtained were collected, including levels of phonological awareness, vocabulary, and non-verbal IQ. The study confirmed a significant deficit in storage and processing skills in the serial recall task in the CI group, as well as different predictors among the two groups. While the variance in serial recall scores for the typical hearing (TH) group was mainly explained by their level of phonological awareness, the performance of the CI group children was better explained by their vocabulary level. The authors discuss the notion of lexical restructuring to explain this difference. According to this theoretical proposition, lexical acquisition involves an initial phase of memorizing holistic forms, with unanalyzed phonological structures, which eventually leads to a mature system composed of well-defined items structured phonologically (Luce & Pisoni, 1998). This restructuring goes hand in hand with a gradually finer processing of the spectro-temporal details of the signal. Given their perceptual limitations that restrict their ability to develop a fine sensitivity to phonetic features and associated phonological structures, children with CIs may encounter difficulties in performing this lexical restructuring. Consequently, the development of their verbal memory may rely on coarse phonological representations, which are less effective for storage.

These explanatory perspectives seem of great interest to us because, on the one hand, they highlight, through the notion of lexical restructuring, that it is possible that the memorization of phonological representations may occur more on underspecified structures for children with CIs, which aligns with our initial hypotheses. On the other hand, the effects on verbal working memory may also help to explain the specific link between phonological and morphosyntactic skills in the children of our studies: the quality of phonological representations has a direct impact not only on phonological accuracy but also on verbal working memory skills. The perception and production of morphosyntactic patterns require the manipulation of precise phonological units that must be maintained in memory long enough to be processed. A significant link between verbal memory performances and linguistic outcomes has been observed in many studies involving children with CIs (Romano et al., 2021; Zhang et al., 2022). Moreover, cognitive processing limitations have also been suggested as interpretative avenues for the morphosyntactic difficulties in children with CIs (Bourdin et al., 2016), particularly in cases of determiner omissions (Szagun, 2001).

2.2. Acoustic-linguistic interface

By introducing a score for the processing of morphophonological alternations based on the presence of nasal or oral vowels in study 5 (*Consonant and vowel production: an integrative study* - chapter 6) and linking speech production patterns with grammatical skills, we aimed to more directly study the impact of the specific perceptual difficulties due to CI limitations on associated grammatical skills. The very specific difficulties found in CI children in processing nasal and oral vowels in grammatical and lexical contexts, compared to other morphophonological oppositions, demonstrate difficulties that are closely related to perceptual challenges.

The strong correlations observed between the score for these morphophonological opposition morphemes (nasal vs. oral vowels) and the MS development score (MLUm) further indicate that children who are more adept at processing fine phonetic details, such as those carried by vowel nasality, are also more likely to achieve higher grammatical production skills. The ability of children to manage and compensate for perceptual limitations through a more effective use of relevant acoustic cues appears to be associated with better linguistic performance. The study of clusters formed by pooling all variables characterizing children in terms of phonetic and linguistic aspects confirms this hypothesis: the group of children with the lowest performance is the one that shows few signs of compensating for the specific difficulties associated to CIs.

3. Effects of implantation age: evidence in favor of sensitive periods of development?

Through the study of the effects of implantation age, numerous findings have been made regarding the CI population, highlighting the need to minimize the period of auditory deprivation, especially in prelingually deaf children, to quickly stimulate the cortical areas dedicated to auditory processing and their connections to language regions. Early implantation thus limits the colonization of auditory areas by other modalities, which can occur due to the brain's plasticity in response to auditory deprivation (Kral et al., 2016, 2019). Numerous studies have demonstrated the beneficial impact of early implantation on language development: some support the benefits of implantation before the age of 2 years (Nicholas & Geers, 2007), others argue that implantation between 12–18 months at the latest is necessary for optimal development (Kral et al., 2019), or even 9 months (Karltorp et al., 2020).

With regard to the studies carried out within this thesis, different effects of implantation age were observed for the different linguistic components evaluated. Indeed, implantation age effects were observed on both perceptive and productive skills for nasal and oral vowels (implantation age of 10 months, studies 1 - *Perception of the vowel nasality feature* - and 2 – *Production of oral and nasal vowels*), on skills in marking the nasal-oral difference (study 3 - *Production of fricative consonants*), on the distinction of the places of articulation for fricatives, and on the presence of high-frequency energy in the frication noise (study 3 - *Production of fricative consonants* - and 4 - *Consonant and vowel production: an integrative study*). Generally, the speech production profiles of early-implanted children were closer to those of children with typical hearing, as shown by the representations of the implantation age groups during the factorial analysis conducted on all acoustic measures (figure 5.5, chapter 5). In contrast, the second factorial analysis, which included linguistic measures in addition to acoustic measures (figure 7.3 – chapter 7), did not show an advantage for early-implanted children: the CI groups (implanted before or after 16 months) were distinctly different from the TH children across the factorial axes. We observed very few effects of implantation age regarding the linguistic components: no effect was observed on phonological scores, naming abilities, or MLUm scores. Only lexical diversity and the use of some function words (auxiliaries, reflexive pronouns) or verb forms (imperfect tense) showed an advantage for earlier-implanted children.

Moreno-Torres and colleagues (Moreno-Torres et al., 2016) tested the hypothesis of the existence of short sensitive periods for the development of "lower-level skills" in speech processing and speech production, in contrast to "higher-level" language skills, which might benefit from a longer sensitive period. They base this hypothesis on the dual-pathway model (Hickok, 2012; Hickok & Poeppel, 2004), which proposes that the brain's speech processing system comprises a dorsal pathway that integrates auditory-motor information required for segmental processing and a ventral pathway that integrates auditory-conceptual information required for lexical processing. While the dorsal pathway uses fine acoustic details to integrate auditory representations with motor patterns, the ventral pathway, primarily dedicated to linking auditory representations to semantic information, relies only on coarse acoustic information. These two pathways normally work together to develop the phonological system, lexical-semantic knowledge, and grammatical skills.

The authors draw on findings in the literature concerning deficits in the development of lower-level skills (presumably more closely associated with the dorsal pathway and characterized by a very short sensitive period of development, according to the authors). In contrast, for higher-level skills, more variability in performance is observed, which may be related to the functioning of the ventral pathway with a longer sensitive period. The authors tested their hypothesis by examining the impact of implantation age and environmental factors (parental involvement and socioeconomic status - SES) on different measures of phonological accuracy and on various linguistic measures in children who received their implants before age 2 compared to their typical hearing peers. Significant correlations were observed between implantation age and the level of precision in producing the place of articulation for consonants, while environmental factors were correlated with linguistic measures (phonological, lexical, and morphosyntactic) as well as measures of precision in the manner of articulation and voicing features.

The authors attributed these differences to the fact that difficulties in processing the acoustic cues relevant for place of articulation are directly related to the CI technical limitations and depend on short sensitive periods in the development of the perceptual system. In contrast, measures related to acoustic features that are better encoded by the cochlear implant (CI) are less dependent on these short developmental periods because they are less affected by the CI's sound coding limitations. Higher-level skills are more closely related to environmental conditions. Indeed, a high SES and strong family involvement provide resources to compensate for CI-related limitations, with CI children in the study benefiting and achieving performances similar to those of typical-hearing children on higher-level linguistic measures. Children less advantaged by their environment developed more slowly, lacking sufficient external support to compensate for their difficulties. According to the authors, developing higher-level skills in children implanted before the age of 2 depends largely on experience.

The differential effects between our implantation age groups on segmental perception and production skills, which are considered ‘lower skills,’ and other skills associated with ‘higher skills’, may support the findings of these authors. Early implantation promotes stimulation of highly demanding perceptual systems associated with processing a degraded and imprecisely coded input by the CI. The authors’ findings could be extended to the compensation strategies discussed in this thesis. Early implantation may promote better adaptation to signal constraints within the ‘lower skills,’ thereby improving the functioning of the brain’s dorsal processing pathway. It is more challenging for us to provide evidence for the involvement of environmental factors, as these were only approached in our study through parental education levels, which showed very few effects, even within the ‘higher skills.’ It is possible that this single measure did not capture the full effect of the environment and family involvement, which could explain some of the variability in performance. However, it is worth noting a higher prevalence of children with low SES levels within the cluster showing the weakest perceptual, productive, and linguistic performances, which could contribute to reflecting on the impact of the environment on overall language skills.

4. Sources of variations: a synthesis model

Before concluding this discussion on the limitations and perspectives of this thesis, we would like to put into perspective the main focus of our work, namely the study of perceptual limitations and their impact on linguistic components, in relation to all the factors involved, directly related to deafness and affecting the language of children with CI. We propose a preliminary integrative model as a basis for discussion (Figure 8.1).

In this synthesis model, it is proposed that deafness associated with cochlear implantation has a direct impact on three elements: first, it delays access to auditory input, thus to an oral language environment; second, it leads to several perceptual limitations even with the support of the implant; and; third, it is likely to cause, at least during the pre-implantation period and in the early post-implantation phase, a limitation in the quantity and possibly the quality of verbal exchanges between the child and their immediate surroundings. These different elements lead to various sources of influence on language development: delayed access to oral language is defined in the model as source A, resulting in a lack of stimulation of the auditory cortical areas and their connections with other language-related areas, thereby impacting language skills. The perceptual limitations related to the degraded auditory signal transmitted by the cochlear implant (CI) lead to sources of influence B, C, and D.

Indeed, these perceptual limitations will impact, on the one hand, phonetic discrimination skills, affecting the quality of phonological representations, which in turn limits the memorization and manipulation of appropriate fully specified phonological forms associated with lexical and grammatical morphemes (source B). On the other hand, these limitations will also affect the ability to process prosodic patterns, especially those carried by variations in fundamental frequency, leading to underspecified prosodic representations and thereby impacting the perception of salient elements in the oral utterances and the whole speech segmentation process (source C). These same difficulties are likely to cause pragmatic challenges (e.g., processing emotional prosody, understanding implicit language), which can also affect language skills by limiting opportunities for complex interactions. Similarly, the perceptual limitations related to sound processing by the CI also have a negative effect on speech perception in noise (source D), potentially reducing the quantity and quality of interactive exchanges in noisy environments commonly encountered in daily life. Source of influence E synthesizes the impact of these different factors and the limited quantity and quality of interactive language exchanges that are crucial for language development.

Based on this provisional integrative model, one can see that the questions that interested us in the context of this work primarily focused on source of influence B (the links between perceptual limitations and language) through the study of the effects of CS exposure, and, to some extent, on source A through the study of the effects of auditory age and implantation age. The effects related to limitations in the development of the prosodic system were also briefly addressed through questions about the prosodic bootstrapping of lexical acquisition and the study of determiner production. However, in order to achieve the "full picture", it would be necessary to consider the countless additional sources of mutual influence that may have played a role in the development mechanisms of the language components investigated, particularly through the medium of pragmatic skills, which are highly dependent on the quality of early and daily interactions to which children are exposed.

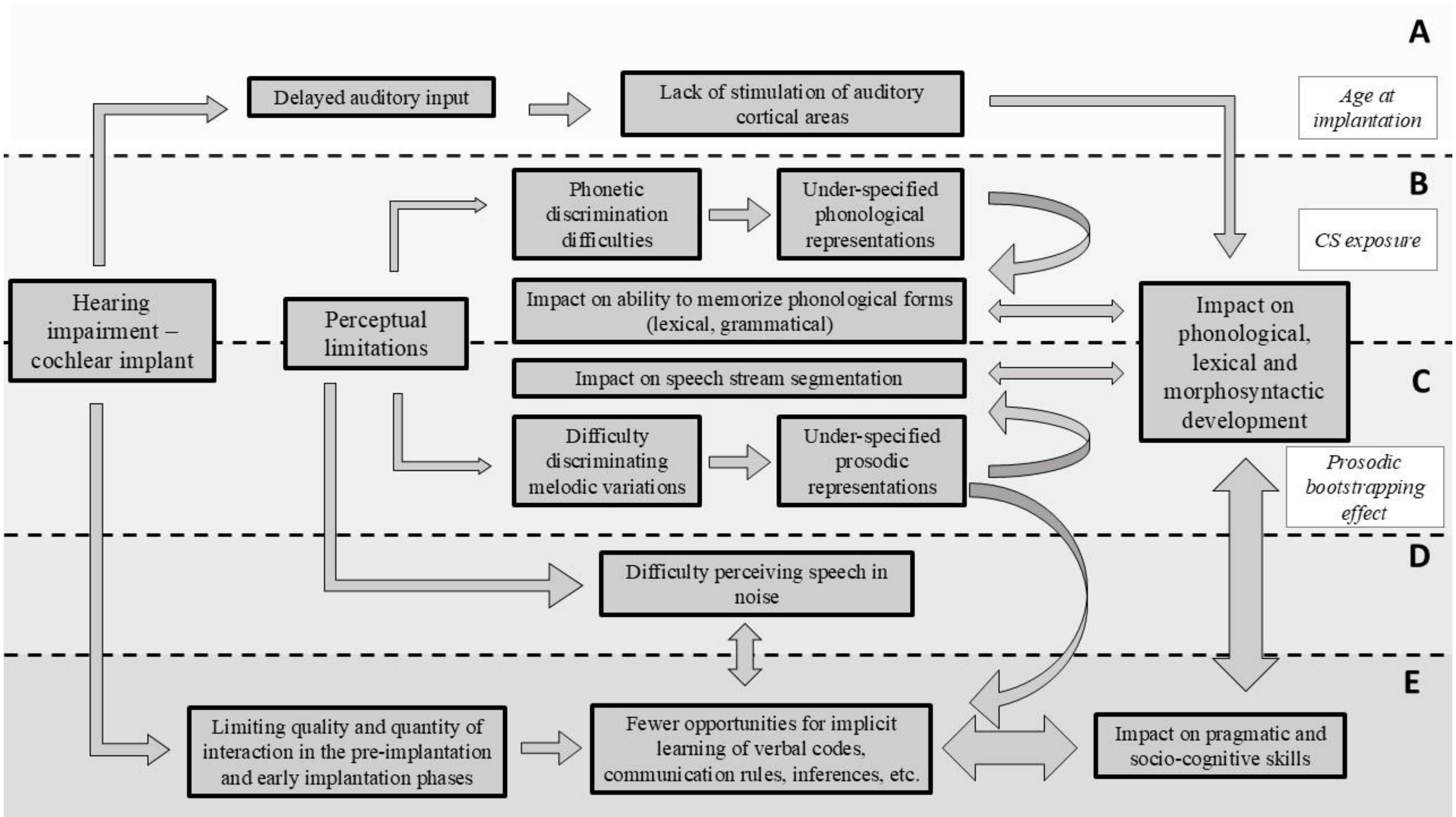

Figure 8.1: Synthetic model of the different sources of influence on language development in deaf children with cochlear implants (CIs). The arrows represent a causal link, and the double arrows represent an interaction effect between elements.

These different sources of variation interact with individual and environmental factors, which can constitute risk or protective factors, a notion borrowed from the environmental models of Bronfenbrenner (1994). In this context, late or unilateral implantation in cases of profound bilateral deafness could be considered risk factors, while the use of multisensory speech perception methods, such as CS, or high parental involvement could constitute protective factors.

Language development involves many sources of variability in typical hearing children, and even more so in deaf children with CI. The work carried out here has led to reflections on the nature of the sources of influence on overall language performance, providing perspectives for clinical and research investment. However, it is obviously necessary to maintain a holistic vision of the child and the different sources of influence on their language and communication development.

5. Clinical implications

The present thesis reveals various findings that raise concerns about the impact of the perceptual limitations of CI on linguistic development but also provide encouraging insights by observing possibilities for compensating for these limitations through the perceptual system.

Clinically, it seems essential to promote, by all means and as early as possible, the use of relevant and well-coded acoustic cues by the child's CI. To achieve this, the activation of multimodal speech perception cues through a method such as Cued Speech appears highly beneficial. However, its implementation must be both early and intensive, requiring significant parental involvement. The high results obtained by a group of children not exposed to CS also lead to questioning other sources that enable children to develop good language skills and utilize perceptual compensation strategies. In this regard, auditory-verbal therapy, a therapeutic approach focusing on training auditory perception, could also be an interesting option. This method is based on the premise that it is necessary to stimulate intensively perceptual auditory pathways and includes sessions with a practitioner and family coaching. The goal is to enhance the child's receptive skills through listening activities and regular assessments of objectives to adjust the follow-up. Recent studies have shown its positive impact on perceptual skills (Binos et al., 2021), similar to exposure to CS (Van Bogaert et al., 2023), suggesting that this approach could also be beneficial. It is entirely possible that by focusing on auditory attention and through the feedback received from people in their environment, the child may be more likely to access relevant acoustic details to discriminate sounds in their environment. It would be interesting to study further the impact of this type of method on the production skills of segments carried by fine acoustic cues to observe whether their positive impact compensates for the perceptual limitations of CIs, similarly to intensive exposure to CS. It should be noted that the parental involvement required by the method may also provide the environmental benefits extensively detailed in the literature. In the same vein, high-variability perceptual training programs also deserve our attention. This well-known technique, which facilitates the acquisition of a second language, is part of an approach based on auditory training by using verbal material from multiple speakers in various phonetic contexts. This method has been proposed to demonstrate consistent long-term progress and a more substantial transfer of skills to production (Lively et al., 1993; Logan et al., 1991). Its application to the cochlear implant population has recently been tested in both adults (Miller et al., 2017) and Mandarin-speaking children (Zhang et al., 2024) and has shown benefits in the perception of lexical tone.

Parental involvement in the interventions for deaf children has been shown to be a crucial factor in language development (Ligny & Ciardelli, 2020; Moeller et al., 2013). Although this factor was not directly studied in this research, it was noted that inconsistent use of Cued Speech (CS) might not provide the benefits of this method for language acquisition (CS- group). It therefore seems essential to align with parents on the appropriate stimulation method, ensuring that they understand and integrate its significance to promote continuity between therapeutic follow-ups and the home environment. In this regard, it is also important to ensure that the approach suits the parents in terms of resources, to avoid implementing methods that may be disregarded in long term.

Furthermore, it seems highly beneficial to develop tools that allow for a detailed assessment of the specific difficulties related to the perceptual limitations of the implant, as well as possible compensation strategies. The acoustic analyses conducted in the present studies have highlighted the preferential use of certain acoustic cues, the observation of which could be highly relevant in diagnosis and clinical follow-up. However, these types of analyses are very time-consuming and not necessarily accessible in practice; therefore, it would be of great interest to develop tools that are accessible to clinicians and focused on these needs. Additionally, the specific links observed between phonological accuracy and morphosyntactic development highlight the importance of ensuring the quality and stability of phonological representations in monitoring children with grammatical difficulties. Appropriate interventions could help to work effectively on the perception and production of morphophonological alternations carried by “at-risk” acoustic correlates.

6. Limitations and future research directions

The various studies presented in this thesis, although providing interesting avenues for reflection, suffer from limitations that require caution when interpreting the results. As with much research on the population of CI users, the two samples of children with CI(s) recruited for the studies were relatively small. With such limited samples, studies of associated characteristics (exposure to Cued Speech, age groups, etc.) are even more restricted. Statistical precautions were implemented to limit uncontrolled random effects related to variability within the groups through modeling with random effects. Nonetheless, the small size of the different subgroups inevitably affects the statistical power and generalizability of the results.

Furthermore, it should be noted that the acoustic analyses conducted in studies 3, 4, 5, and 6 were based on productions from a naming task in which it was not possible to control the phonetic and syllabic context of each target segment — the objective was mainly to select frequent words with a low age of acquisition. It is essential to control these aspects in acoustic analyses. However, precautions were also taken in this regard: for example, by eliminating the extreme part at the beginning and at the end of the segment for vowels and fricative consonants, and by using a multitaper spectrum to limit the impact of coarticulation effects on fricatives. The Voice Onset Time measurements, however, could have been affected by both the phonetic context and the speech rate of the children; thus, the results should be interpreted with caution.

Finally, a major limitation of the study is the lack of information regarding the children’s family environment, particularly the level of parental involvement in care and the level of verbal stimulation received in the family context. These variables could have had a considerable uncontrolled impact on the study and may have contributed to some unexpected results. The impact of these elements could be further documented in future studies.

7. Conclusion

Beyond the observations of significant difficulties related to deafness and the processing of sound by the CI, the various studies carried out in the context of the present thesis also highlighted the substantial capacity of the perceptual system to adapt to the degraded sound signal and to compensate for difficulties through effective strategies. There is inter-individual variability in the use of these strategies, which can be partially traced to the methods of management (advantage of CS) and the timing of implantation.

Meaningful connections between these adaptive skills and linguistic abilities were also identified, with first overall phonological performance being linked to MS performance, and second profile analyses including all linguistic skills resulting in some profiles that combine poor adaptive capacity with weak linguistic performance. It seems essential to focus on the perceptual system's compensation mechanisms to encourage their use in the care and monitoring of children with CIs.

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Appendix 1

Information and consent form.

Information et consentement éclairé: Développement langagier d'enfants présentant une surdité et porteurs d'implant(s) cochléaire(s) et d'enfants normo-entendants

Fiche d'information

Présentation du cadre de la recherche

Cette recherche est réalisée dans la thèse de doctorat de Sophie Fagniart, menée à l'UMONS au sein du Service de Métrologie et Sciences du Langage.

Avant d'accepter de participer à cette recherche, merci de prendre le temps de lire les informations qui suivent. Ce formulaire vous explique les buts de ce projet de recherche et sa procédure. Il indique les coordonnées de la personne à contacter en cas de besoin. **N'hésitez pas à poser toutes les questions** que vous jugerez utiles à la personne qui vous présente ce document.

Nature de l'étude

L'étude vise à étudier la manière dont différents aspects du langage (la production des sons, l'acquisition du vocabulaire, la production des phrases) se développent chez de jeunes enfants présentant une surdité et porteurs d'implant(s) cochléaire(s), en comparaison avec les mêmes compétences investiguées chez des enfants normo-entendants du même âge.

De nombreuses études ont étudié différents aspects du langage chez les enfants présentant une surdité, mais peu ont étudié comment celles-ci se développaient ensemble. Or, par exemple, on peut soupçonner qu'un enfant présentant des difficultés à percevoir/produire certains sons de sa langue pourrait avoir des difficultés à comprendre/produire des phrases contenant ces classes de sons. Il est donc tout à fait intéressant d'évaluer dans une même étude ces différents aspects du langage chez des enfants à différents âges, et ce aussi bien chez des enfants présentant une surdité que chez des enfants n'ayant pas de difficultés auditives.

Déroulement de la participation

La participation à la recherche comprendra une séance d'approximativement 45 minutes, durant laquelle il sera demandé à l'enfant de nommer des images, de raconter une histoire à l'aide d'un support et de pointer une image en fonction de phrases entendues.

Au cours de cette séance,

☐ la voix de votre enfant sera enregistrée ;

☐ avec votre accord, votre enfant sera filmé (si vous ne souhaitez pas qu'il soit filmé, nous pourrons uniquement utiliser les enregistrements audio pour nos analyses) ;

☐ des renseignements concernant votre enfant seront collectés (p.ex. : environnement scolaire, familial, activités, ...) ;

☐ des informations relatives à la santé de votre enfant seront collectées (p.ex. : développement psychomoteur, antécédents médicaux, ...).

Information et consentement éclairé: Développement langagier d'enfants présentant une surdité et porteurs d'implant(s) cochléaire(s) et d'enfants normo-entendants

Avantages, risques ou inconvénients possibles liés à la participation de votre enfant

Votre participation à cette recherche permettra de faire progresser les connaissances scientifiques concernant le développement du langage en général, et chez l'enfant présentant une surdité et porteur d'implant(s) cochléaire(s) en particulier. De plus, mieux comprendre comment se développent les capacités à produire des sons, produire des mots et des phrases permettra de contribuer à développer des outils plus précis pour l'évaluation langagières des enfants, et ainsi aider les praticiens à orienter les moyens de prise en charge.

Il est possible que le fait de réaliser la tâche demandée induise chez votre enfant une certaine fatigue, un certain stress, etc. Si cela se produit, l'enfant ne doit pas hésiter à en parler avec la personne qui mène l'entrevue. Au besoin, celle-ci pourra ajuster les modalités de passation et, le cas échéant, vous suggérer une liste des ressources disponibles dans votre région.

Participation volontaire et droit de retrait

Vous êtes libre de participer à ce projet. Vous pouvez refuser de répondre à certaines questions, de vous soumettre à certaines procédures, ou encore **mettre fin à votre participation à tout moment**, sans avoir à fournir de raisons et sans aucun préjudice. Si vous décidez de mettre fin à votre participation à l'étude, il est important d'en prévenir la personne responsable de la recherche (voir coordonnées ci-dessous). Celle-ci vérifiera auprès de vous si vous acceptez que vos données soient conservées pour l'étude ou si vous préférez qu'elles soient détruites.

Confidentialité et gestion des données

Dans les travaux et supports pédagogiques produits à partir de cette recherche, votre enfant ne sera **jamais identifié(e)** par son nom/prénom/initiales, mais par un code aléatoire (p.ex. Sujet 34). Les enregistrements audio et vidéo et leurs transcriptions seront traités afin de réduire au maximum les informations permettant de l'identifier (p.ex. bruitage des noms propres).

Les données personnelles collectées (nom, prénom, etc.) seront dissociées des autres données (enregistrements, données instrumentales) par "pseudonymisation" et seul le chercheur responsable aura accès à la clé permettant de les associer. Cette clé sera détruite avant une éventuelle mise à disposition des données auprès de chercheurs non associés au Service de Métrologie et Sciences du Langage de l'Université de Mons.

Tous les matériaux de la recherche (incluant les données pseudonymisées et enregistrements) seront conservés **de manière sécurisée** grâce à l'infrastructure fournie par l'Université de Mons.

Dans l'intérêt public, ces matériaux pourront éventuellement être mis à disposition d'autres chercheurs n'ayant pas directement participé à la présente recherche. Dans ce cas, un accès **restreint** sera supervisé par une infrastructure sécurisée répondant aux standards européens les plus élevés en termes de gestion de données de recherche et d'accès authentifié à celles-ci (p.ex. plateforme CLARIN).

Information et consentement éclairé: Développement langagier d'enfants présentant une surdité et porteurs d'implant(s) cochléaire(s) et d'enfants normo-entendants

Renseignements supplémentaires/Contact

Si vous avez des questions sur la recherche ou sur les implications de votre participation, si vous souhaitez vous retirer du projet ou désirez transmettre d'éventuels documents, veuillez contacter le chercheur responsable : Fagniart Sophie, logopède et assistante-doctorante à l'UMONS (0479/82 35 55 – sophie.fagniart@umons.ac.be).

Remerciements

Votre collaboration est très précieuse pour cette recherche et nous vous remercions vivement d'y participer.

Les résultats de la recherche seront disponibles lorsque le traitement des données sera réalisé. Si vous souhaitez recevoir un résumé des résultats, merci de préciser l'adresse postale ou électronique à laquelle vous le faire parvenir :

Adresse 1____

Adresse 2____

Mentions légales

La confidentialité est assurée sur bases des limites prescrites par les lois belges et européennes.

Le Responsable légal du traitement des données personnelles est l'Université de Mons, Place du Parc, 20 à 7000 Mons. Vous avez le droit de prendre connaissance des données vous concernant et de demander la rectification d'éventuelles données inexactes.

Pour tout renseignement en matière de vie privée, la Déléguée à la Protection des Données est Mme Graciela SCHIFFINO (UMONS, Place du Parc, 23 – 7000 MONS – dpo@umons.ac.be; 065/37.37.02).

Le cas échéant, vous pouvez introduire une réclamation auprès de l'Autorité de Protection des Données (https://www.autoriteprotectiondonnees.be).

Information et consentement éclairé: Développement langagier d'enfants présentant une surdité et porteurs d'implant(s) cochléaire(s) et d'enfants normo-entendants

Formulaire de consentement (représentant légal)

Je soussigné(e) ____

autorise ____ à participer à la recherche intitulée : « Etude du développement langagier auprès d'enfants présentant une surdité et porteurs d'implant(s) cochléaire(s) et d'enfants normo-entendants». J'ai pris connaissance du formulaire et j'ai compris le but, la nature, ainsi que les éventuels avantages, risques et inconvénients du projet de recherche.

Je suis satisfait(e) des explications, précisions et réponses que le chercheur m'a fournies, le cas échéant, quant à ma participation à ce projet.

Date: __________________________________

Titre (père, mère, tuteur, curateur, etc.):______________________________________

Signature:

Appendix 2

Information letter.

Lettre d'information à destination des parents des enfants recrutés pour une étude portant sur le développement du langage d'enfants présentant une surdité et porteurs d'implant(s) cochléaire(s)

Etude réalisée dans le cadre de la thèse de doctorat de Fagniart Sophie – UMONS – en collaboration avec le centre « Comprendre et parler ».

Madame, Monsieur,

Nous vous proposons de participer à une étude réalisée dans le cadre de la thèse de doctorat de Fagniart Sophie, réalisée à l'UMONS en collaboration avec le « Centre Comprendre et Parler ».

Cette lettre a pour objectif de vous donner des explications concernant l'étude et son déroulement. Vous pourrez prendre le temps de consulter ces informations afin de réfléchir à votre participation, mais aussi de poser vos questions auprès de l'investigatrice principale, Fagniart Sophie, que vous pouvez joindre par mail (sophie.fagniart@umons.ac.be) ou par téléphone (0479/82 35 55).

Quels sont les objectifs de l'étude ?

L'étude vise à étudier la manière dont différents aspects du langage (la production des sons, l'acquisition du vocabulaire, la production des phrases) se développent chez de jeunes enfants présentant une surdité et porteurs d'implant(s) cochléaire(s), en comparaison avec les mêmes compétences investiguées chez des enfants normo-entendants du même âge.

De nombreuses études ont étudié différents aspects du langage chez les enfants présentant une surdité, mais peu ont étudié comment celles-ci se développaient ensemble. Or, par exemple, on peut soupçonner qu'un enfant présentant des difficultés à percevoir/produire certains sons de sa langue, pourrait avoir des difficultés à comprendre/produire des phrases contenant ces classes de sons. Il est donc tout à fait intéressant d'étudier dans une même étude ces différents aspects du langage chez des enfants à différents âges, et ce aussi bien chez des enfants présentant une surdité que chez des enfants n'ayant pas de problèmes d'audition.

Mieux comprendre comment se développent les capacités à produire des sons, produire des mots et des phrases permettra de contribuer à développer des outils plus précis pour l'évaluation langagières des enfants, et ainsi aider les praticiens à orienter les moyens de prise en charge.

Comment se déroulera l'étude ?

L'investigatrice de l'étude, Fagniart Sophie, rencontrera votre enfant et lui proposera de réaliser quatre épreuves. L'ensemble de la passation devrait durer de 30 à 45 minutes.

Les épreuves consisteront en :

1) *Une tâche de dénomination sur base d'image* : Lors de cette épreuve, des images seront présentées à votre enfant, et celui-ci devra dire le mot de ce qui est représenté sur l'image. 48 images lui seront présentées au total, et des indices seront donnés afin de l'aider en cas de difficultés. Les mots choisis sont des mots fréquents au sein du vocabulaire des enfants. L'objectif de cette tâche est d'étudier la façon dont les enfants produisent des mots de vocabulaire, et la façon dont ils produisent les sons qui constituent ces mots.
2) *Une première tâche de production de récit sur base d'images – avec modèle préalablement présenté :* Lors de cette seconde épreuve, une histoire sera présentée à votre enfant, au moyen d'un film présentant une personne racontant l'histoire, accompagnée d'images animées. A la fin de la présentation de l'histoire, votre enfant sera invité à raconter lui-même l'histoire qu'il a entendue, avec l'aide des images animées qu'il aura déjà vue. Il sera précisé à votre enfant qu'il ne doit pas s'inquiéter s'il ne se rappelle pas de toute l'histoire, car il pourra s'aider des images et inventer si besoin. L'objectif de cette tâche est d'étudier la façon dont les enfants produisent des mots et des phrases au sein d'une histoire.
3) *Une tâche de désignation d'images sur input oral :* Lors de cette épreuve, votre enfant entendra des mots ou de petites phrases, qu'il devra d'abord répéter. Ensuite, il devra choisir, parmi deux images, laquelle correspond à ce qu'il a entendu. Cette épreuve vise à étudier la façon dont les enfants peuvent percevoir et traiter de légères différences qui peuvent distinguer certains mots ou phrases (par exemple : bateau/bâton, il prend/ils prennent).
4) *Une seconde tâche de production de récit sur base d'un livre imagé :* Pour cette dernière épreuve, il sera demandé à votre enfant de raconter une histoire à l'aide d'un livre contenant des images. Cette fois-ci, votre enfant n'aura pas entendu une histoire racontée auparavant et sera donc libre de raconter l'histoire en suivant le livre imagé. Cette épreuve permettra également d'étudier la production des mots et des phrases de votre enfant, mais dans un contexte plus libre.

Afin de pouvoir analyser précisément les résultats aux épreuves, des informations seront recueillies à propos de votre enfant, afin d'en savoir plus, entre autre, sur son type de surdité, son âge d'implantation, son niveau de langage, mais aussi sur son environnement familial et scolaire. Pour cela, nous complèterons avec vous différents questionnaires, et des informations pourront être collectées auprès de vos praticiens du centre « Comprendre et Parler ».

__Enregistrement audio et vidéo des épreuves__

Les productions de votre enfant seront enregistrées au moyen d'un magnétophone, ce qui permettra de les analyser par la suite. Pour pouvoir analyser le plus précisément possible le langage de votre enfant durant les épreuves, nous souhaiterions pouvoir également filmer la passation.

Si vous ne souhaitez pas que des enregistrements vidéos soient faits pendant les épreuves, nous le comprendrons tout à fait et pourrons alors uniquement procéder aux enregistrements audio.

Les informations et enregistrements seront-ils confidentiels ?

Les enregistrements audio et vidéo seront strictement rendus anonymes et leurs contenus seront protégés. Seules les personnes directement impliquées dans l'étude, en ce compris l'investigatrice principale et les praticiens du centre « Comprendre et Parler », connaîtront l'identité de votre enfant. En effet, lors des analyses, votre enfant recevra un code d'identification afin que son nom n'apparaisse plus et qu'il ne puisse pas être identifié par des tierces personnes. Si des extraits des vidéos devait être utilisés au sein de communications scientifiques, le visage de votre enfant sera flouté afin d'éviter toute possibilité de le reconnaître. Les enregistrements et documents informatifs seront stockés au sein de dispositifs informatiques sécurisés et protégés.

Si vous le souhaitez, les résultats obtenus par votre enfant pourront être communiquées aux praticiens du centre « Comprendre et Parler » avec lesquels votre enfant est en contact, afin de pouvoir compléter les évaluations déjà réalisées et ainsi contribuer au suivi de votre enfant.

Comment se passera la participation à l'étude ?

Si vous décidez de participer à l'étude, vous serez contactés et/ou pourrez directement entrer en contact avec Sophie Fagniart, qui déterminera avec vous les moments qui conviennent le mieux pour réaliser la passation des épreuves. Il sera également possible de discuter du lieu le plus approprié pour la réalisation des testings : il est possible de les réaliser à votre domicile à votre meilleure convenance, ou sur rendez-vous au centre « Comprendre et Parler ».

Lors du rendez-vous, il vous sera demandé de compléter un document de consentement éclairé, qui attestera du fait que vous participez à l'étude sur base volontaire et que vous avez été informé du déroulement de l'étude. Ce document ne constitue aucunement en une obligation de participation : vous pouvez, à tout moment, décider de vous retirer de l'étude sans avoir à vous justifier auprès de l'investigatrice ou des praticiens du centre « Comprendre et Parler ».

Précautions sanitaires

Lors de la rencontre avec votre enfant, que celle-ci ait lieu à votre domicile ou au centre « Comprendre et Parler », toutes les précautions sanitaires seront prises afin d'éviter des risques de propagation des maladies transmissibles, en ce compris le COVID-19. Pour ce faire, l'investigatrice de l'étude que vous rencontrerez sera équipée d'un masque et d'une visière, et le matériel et les surfaces de contact seront nettoyés et désinfectés.

Qui contacter en cas de questions ?

Pour toute information complémentaire, n'hésitez pas à contacter Sophie Fagniart à l'adresse mail suivante : sophie.fagniart@umons.ac.be ou au numéro de téléphone suivant : 0479/823555.

Nous vous remercions très chaleureusement pour l'attention que vous porterez à cette étude.

Appendix 3

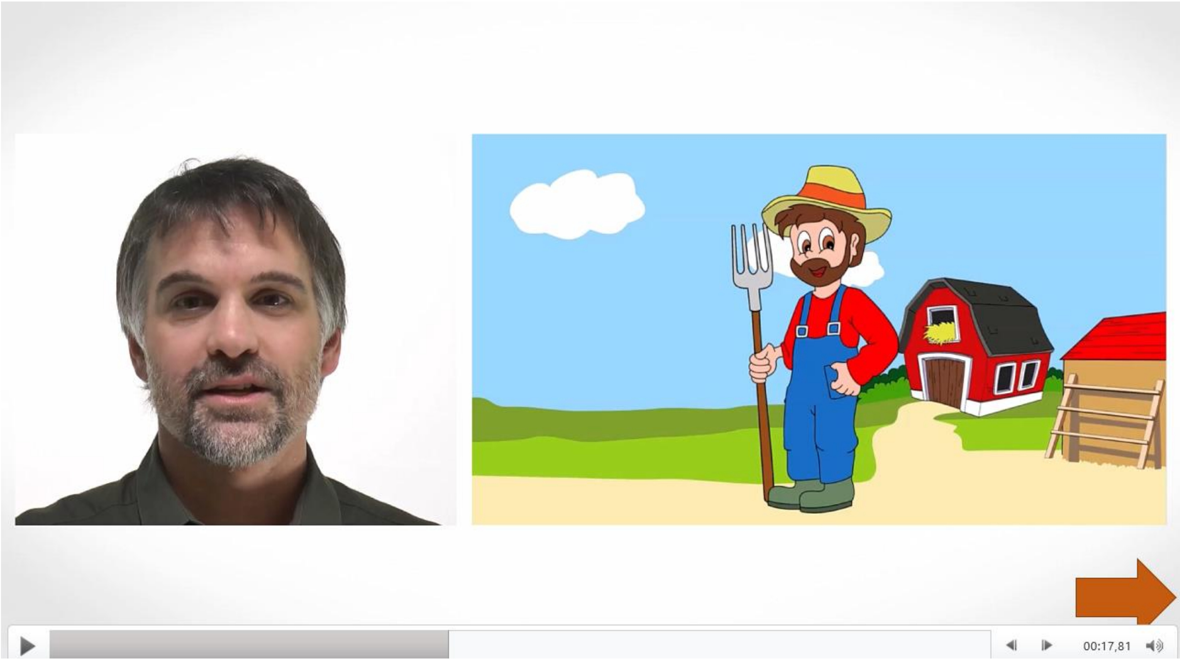
List of target words for the picture-naming task (Studies 3, 4, 5, 6).

Item	Target word
1	Coucou ([kuku]) / Peekaboo
2	Langue ([lɑ̃g]) / Tongue
3	Cheveux ([ʃ(ə)vø]) / Hair
4	Nombril ([nɔ̃bʁil]) / Belly button
5	Pyjama ([piʒama]) / Pajamas
6	Echarpe ([eʃaʁp]) / Scarf
7	Pomme ([pɔm]) / Apple
8	Robe ([ʁɔb]) / Dress
9	Glace ([glas]) / Ice cream
10	Souris ([suʁi]) / Mouse
11	Livre ([livʁ]) / Book
12	Yaourt ([ja.uʁt]) / Yogurt
13	Fleur ([flœʁ]) / Flower
14	Cadeau ([kado]) / Gift
15	Porte ([pɔʁt]) / Door
16	Tortue ([tɔʁty]) / Turtle
17	Poisson ([pwasɔ̃]) / Fish
18	Etoile ([etwal]) / Star
19	Oiseau ([wazo]) / Bird
20	Chaussure ([ʃosyʁ]) / Shoe
21	Chaise ([ʃɛz]) / Chair
22	Crayon ([kʁɛjɔ̃]) / Pencil
23	Pantalon ([pɑ̃talɔ̃]) / Pants
24	Eléphant ([elefɑ̃]) / Elephant
25	Chien ([ʃjɛ̃]) / Dog
26	Cuillère ([kɥijɛʁ]) / Spoon
27	Girafe ([ʒiʁaf]) / Giraffe
28	Téléphone ([telefɔn]) / Telephone
29	Parapluie ([paʁaplɥi]) / Umbrella
30	Escalier ([ɛskalje]) / Staircase
31	Feuille ([fœj]) / Leaf
32	Doigt ([dwa]) / Finger
33	Banane ([banan]) / Banana
34	Panier ([panje]) / Basket
35	Grenouille ([gʁənuj]) / Frog
36	Arbre ([aʁbʁ]) / Tree
37	Train ([tʁɛ̃]) / Train

38	Vache ([vaʃ]) / Cow
39	Carotte ([kaʁɔt]) / Carrot
40	Zèbre ([zɛbʁ]) / Zebra
41	Cloche ([klɔʃ]) / Bell
42	Champignon ([ʃɑ̃piɲɔ̃]) / Mushroom
43	Peigne ([pɛɲ]) / Comb
44	Bras ([bʁɑ]) / Arm
45	Parc ([paʁk]) / Park
46	Fourmi ([fuʁmi]) / Ant
47	Pingouin ([pɛ̃gwɛ̃]) / Penguin
48	Fromage ([fʁɔmaʒ]) / Cheese

Appendix 4

Illustration of the interface used for the induced narration task (Studies 5 and 6) (top) and the complete narrative (bottom). The lines delineate the sections of the narrative illustrated by the same animation sequence.



Il était une fois un fermier. Il s'appelait Jean. Jean vivait dans une ferme. Tous les jours, dans sa ferme, Jean s'occupait de ses animaux : il ramassait les œufs pondus par les poules, il tirait le lait de la vache, il lavait les cochons, il brossait le cheval.

Once upon a time, there was a farmer. His name was Jean. Jean lived on a farm. Every day, on his farm, Jean took care of his animals: he collected the eggs laid by the hens, milked the cow, washed the pigs, and brushed the horse.

Dans les champs, il récoltait la paille, le maïs et le blé avec son tracteur.

In the fields, he harvested straw, corn, and wheat with his tractor.

Dans son potager, il récoltait les légumes : les carottes, les haricots, les petits pois, les pommes de terre, …

In his vegetable garden, he harvested vegetables: carrots, beans, peas, potatoes, ...

Au marché, il vendait ses produits ; la boulangère du village lui achetait son blé, ses œufs, son lait et le boulanger lui achetait ses légumes : les carottes, les haricots, les petits pois, …

At the market, he sold his products; the village baker bought his wheat, eggs, and milk, and the baker bought his vegetables: carrots, beans, peas, ...

Il était bien dans sa ferme, mais il avait une idée dans sa tête, il avait très envie de vivre en ville ! Jean se disait : “Si je vivais en ville, je pourrais faire tant de choses ! »

He was happy on his farm, but he had an idea in his mind, he really wanted to live in the city! Jean thought: “If I lived in the city, I could do so many things!”

“Je me baladerais dans les rues animées, je verrais plein de gens bien habillés, j’achèterais de belles choses dans des beaux magasins. »

“I would walk around lively streets, I would see many well-dressed people, I would buy beautiful things in nice stores.”

Un jour, il trouve un trésor dans son jardin ! Oh, plein de pièces d’or !

One day, he finds a treasure in his garden! Oh, lots of gold coins!

Avec son trésor, il peut faire ce dont il a envie : il achète un appartement dans une grande ville.

With his treasure, he can do what he wants: he buys an apartment in a big city.

Que c’est beau ! Il y a de grands immeubles, il y a du monde partout, il y a des belles voitures et de beaux camions !

How beautiful it is! There are tall buildings, there are people everywhere, there are beautiful cars and nice trucks!

Malgré sa joie du début, au bout de quelques temps, Jean commence à s’ennuyer. Le bruit des voitures et des camions l’énerve, les gens ne sont pas aussi gentils qu’il le pensait…

Despite his initial joy, after some time, Jean begins to feel bored. The noise of the cars and trucks annoys him, and people are not as nice as he thought...

Jean se sent seul, ses animaux lui manquent. Il aimerait trouver du calme et décide de se balader dans le parc. Il s’assied sur un banc, il est très triste.

Jean feels lonely, he misses his animals. He would like to find some peace and decides to take a walk in the park. He sits on a bench, feeling very sad.

Une belle dame s’assied à côté de lui et lui demande : “Bonjour, je m’appelle Jeanne. Comment allez-vous mon cher monsieur ? Vous avez l’air si triste !” “Bonjour, moi c’est Jean. Vous avez raison, je suis très triste. J’ai toujours voulu vivre en ville, mais je ne trouve plus ça si bien maintenant… Et vous, qu’en pensez-vous ? ”

A beautiful lady sits next to him and asks: "Hello, my name is Jeanne. How are you, my dear sir? You look so sad!" "Hello, I'm Jean. You are right, I am very sad. I always wanted to live in the city, but I don't find it so great anymore... And you, what do you think ?"

Jeanne répond : "Ah que je vous comprends ! Moi, je serai si heureuse d'aller vivre à la ferme".

Jeanne replies: "Oh, I understand you! I would be so happy to go live on a farm."

"Je travaillerai dans la ferme, et j'aurai beaucoup d'animaux : je tondrai des moutons pour faire de beaux pulls, je ramasserai les bons œufs des poules, je promènerai des chiens et chats, j'aurai un tracteur pour ramasser le blé, je vendrai mes produits au marché, …"

"I would work on the farm, and I would have many animals: I would shear sheep to make beautiful sweaters, collect the good eggs from the hens, walk dogs and cats, have a tractor to harvest the wheat, and sell my products at the market, ..."

Quelques mois plus tard, Jean et Jeanne sont tombés très amoureux, et se sont mariés.

A few months later, Jean and Jeanne fell deeply in love and got married.

Ensemble, ils ont décidé de retourner vivre à la ferme de Jean.

Together, they decided to go back to live on Jean's farm.

Ainsi, tous les jours, ils s'occuperont des animaux : ils tondront les moutons, ils brosseront les chevaux, ils laveront les cochons. Ils iront au marché vendre leurs produits, ils se baladeront en tracteur dans les champs. Ils seront très heureux, à deux dans leur ferme.

So, every day, they will take care of the animals: they will shear the sheep, brush the horses, and wash the pigs. They will go to the market to sell their products, and they will ride their tractor in the fields. They will be very happy, the two of them on their farm.

Appendix 5

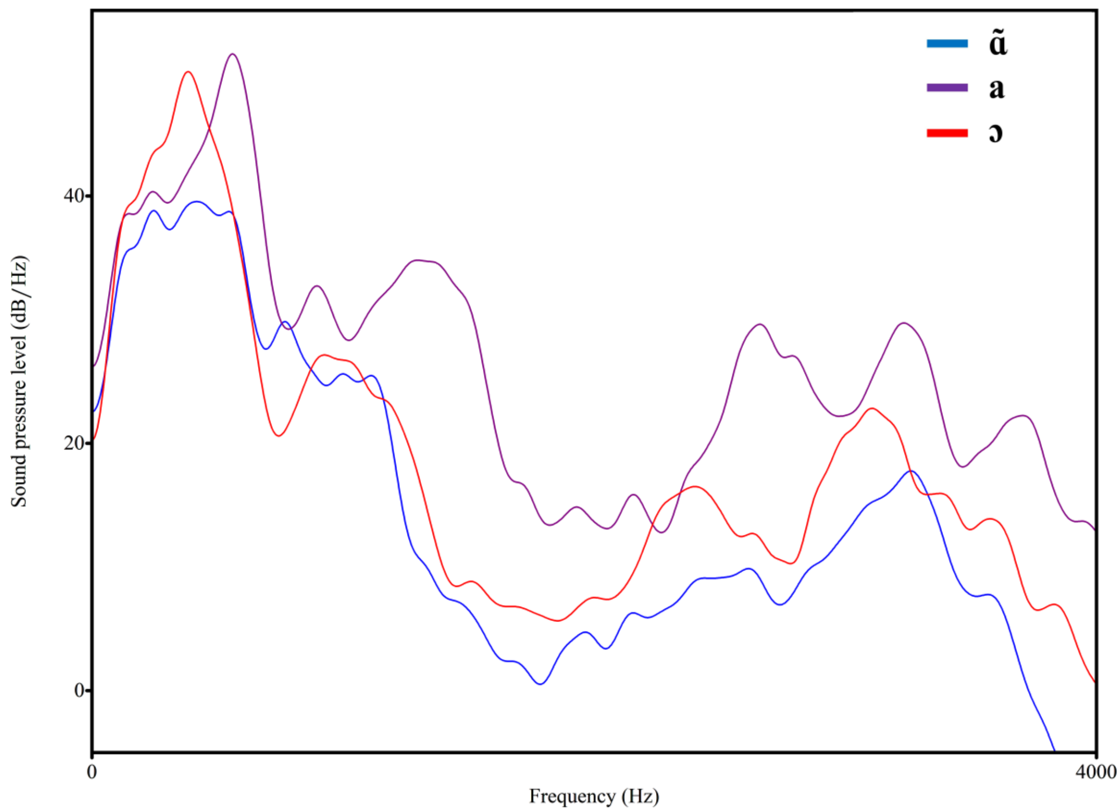
Illustration of the interface used for the sentence/word picture-matching task (Studies 5 and 6) for the first item (top) and the list of different stimuli presented (bottom).

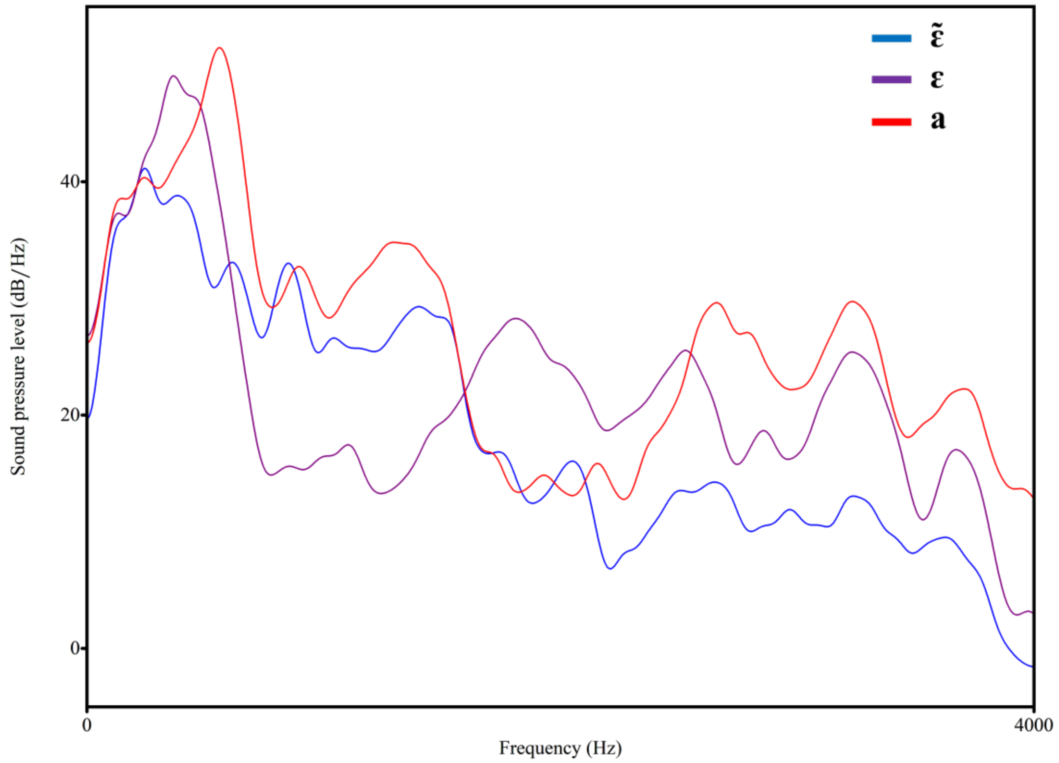
Item	Picture 1	Picture 2
1	Il fait un gâteau ([il fɛ ɛ̃ gato]) / He is making a cake	Ils font un gâteau ([il fɔ̃ ɛ̃ gato]) / They are making a cake
2	Les motos ([le mɔto]) / The motorcycles	Les manteaux ([le mɑ̃to]) / The coats
3	Boulanger ([bulɑ̃ʒe]) / Baker (male)	Boulangère ([bulɑ̃ʒɛʁ]) / Baker (female)
4	Il aimait ([il ɛmɛ]) / He loved	Ils aimaient ([il ɛmɛ]) / They loved
5	Bain ([bɛ̃]) / Bath	Banc ([bɑ̃]) / Bench
6	Ils vont ([il vɔ̃]) / They go	Il va ([il va]) / He goes
7	Il brossera ([il bʁɔsəʁa]) / He will brush	Ils brosseront ([il bʁɔsəʁɔ̃]) / They will brush
8	Les chiens ([le ʃjɛ̃]) / The dogs	Les chiennes ([le ʃjɛn]) / The female dogs
9	Il les lave ([il le lav]) / He washes them	Il le lave ([il lə lav]) / He washes it
10	Blanc ([blɑ̃]) / White	Blond ([blɔ̃]) / Blond
11	Il avait vu ([il avɛ vy]) / He had seen	Ils avaient vu ([il avɛ vy]) / They had seen
12	Les champs ([le ʃɑ̃]) / The fields	Les chats ([le ʃa]) / The cats

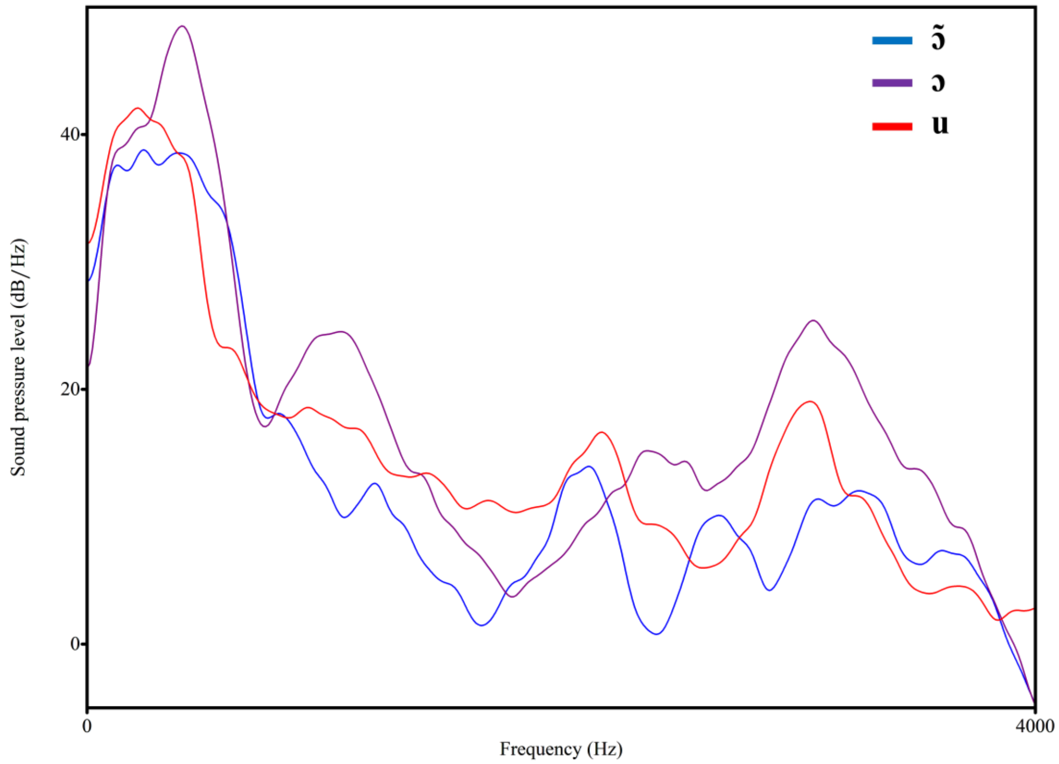
13	Elle dort ([ɛl dɔʁ]) / She sleeps	Elles dorment ([ɛl dɔʁm]) / They sleep
14	Amoureux ([amuʁø]) / In love (male)	Amoureuse ([amuʁøz]) / In love (female)
15	Les mentons ([le mɑ̃tɔ̃]) / The chins	Les manteaux ([le mɑ̃to]) / The coats
16	Jeanne ([ʒan]) / Jeanne	Jean ([ʒɑ̃]) / Jean
17	Ils tondront ([il tɔ̃dʁɔ̃]) / They will mow	Il tondra ([il tɔ̃dʁa]) / He will mow
18	Blanc ([blɑ̃]) / White	Blond ([blɔ̃]) / Blond
19	Il la brosse ([il la bʁɔs]) / He brushes her	Il le brosse ([il lə bʁɔs]) / He brushes it
20	Les champs ([le ʃɑ̃]) / The fields	Les chats ([le ʃa]) / The cats
21	Elle les promène ([ɛl le pʁɔmɛn]) / She walks them	Elle le promène ([ɛl lə pʁɔmɛn]) / She walks him
22	Les pains ([le pɛ̃]) / The breads	Les pas ([le pɑ]) / The steps
23	Chevaux ([ʃəvo]) / Horses	Cheval ([ʃəval]) / Horse
24	Il promène ses chiens ([il pʁɔmɛn se ʃjɛ̃]) / He walks his dogs	Il promène son chien ([il pʁɔmɛn sɔ̃ ʃjɛ̃]) / He walks his dog
25	Heureuse ([øʁøz]) / Happy (female)	Heureux ([øʁø]) / Happy (male)
26	Les lapins ([le lapɛ̃]) / The rabbits	Les lapines ([le lapin]) / The female rabbits
27	Œuf ([œf]) / Egg	Œufs ([ø]) / Eggs
28	Elle pond ([ɛl pɔ̃]) / She lays	Elles pondent ([ɛl pɔ̃d]) / They lay

Appendix 6

Appendix Figure 1a,b,c (Study 1): Spectra representing the stimuli used for discrimination and identification tasks. Each figure shows a nasal vowel (blue line) and its phonological (purple line) or phonetic (red line) oral correspondent.




ɛ̃
ɛ
a
40
20
0
Sound pressure level (dB/Hz)
0
4000
Frequency (Hz)


ɔ̃
ɔ
u
40
20
0
Sound pressure level (dB/Hz)
0
4000
Frequency (Hz)

Appendix 7

Appendix 7 Table 1 (Study 1): Rank Biserial Correlation Coefficients Between Identification Score and Different Acoustic Cues Collected for Vowel 1 and Vowel 2 of the Stimuli. Moderate correlations (between 0.3 and 0.5; Cohen, 1988) are italicized and strong correlations (greater than or equal to 0.5; Cohen, 1988) are in bold.

Vowel position	Acoustic cue type	Acoustic cue	CI group	CI/CS- group	CI/CS+ group	TH group
1	**Frequency**	**F1 (Hz)**	0.150	0.110	0.220	0.240
		F2 (Hz)	-0.250	-0.260	-0.240	*-0.480*
		F2 (Hz)	-0.250	-0.290	-0.180	-0.150
	Bandwidth	**bF1 (Hz)**	0.270	0.290	0.240	**0.610**
		bF2 (Hz)	0.110	0.220	-0.090	-0.050
		bF3 (Hz)	0.070	-0.006	0.230	*0.350*
	Amplitude	**aF1 (dB)**	*-0.310*	*-0.310*	*-0.330*	**-0.640**
		aF2 (dB)	0.140	0.020	*0.380*	**0.510**
		aF3 (dB)	-0.240	-0.270	-0.190	**-0.550**
	Nasal poles detection	**A1-P0 (dB)**	-0.090	-0.140	-0.010	*-0.300*
		A1-P1 (dB)	*-0.320*	*-0.310*	*-0.380*	**-0.560**
	Overall vowel intensity (dB)		*-0.360*	*-0.420*	-0.260	*-0.490*
	Temporal enveloppe (dB)		-0.190	*-0.310*	0.010	-0.060
2	**Frequency**	**F1 (Hz)**	0.060	-0.050	0.270	*0.440*
		F2 (Hz)	-0.160	-0.190	-0.110	-0.290
		F3 (Hz)	-0.140	-0.240	0.020	0.020
	Bandwidth	**bF1 (Hz)**	0.270	*0.340*	0.160	*0.410*
		bF2 (Hz)	0.050	0.140	-0.110	0.000
		bF3 (Hz)	0.030	0.040	0.010	0.140
	Amplitude	**aF1 (dB)**	-0.170	-0.210	-0.090	*-0.420*
		aF2 (dB)	-0.020	-0.130	0.180	0.240
		aF3 (dB)	*-0.300*	*-0.390*	-0.140	*-0.310*
	Nasal poles detection	**A1-P0 (dB)**	-0.230	*-0.300*	-0.110	*-0.380*
		A1-P1 (dB)	-0.130	-0.120	-0.170	-0.240
	Overall vowel intensity (dB)		-0.250	*-0.310*	-0.140	*-0.360*
	Temporal enveloppe (dB)		-0.100	-0.200	0.090	-0.090
Overall stimuli temporal enveloppe (dB)			-0.17	*-0.3*	0.05	0.17

Appendix 7 Table 2 (Study 1) : Eta-squared values associated with d' discrimination scores and the distances between the nasal/oral pairs of the acoustic cues collected for vowel 1 and vowel 2 of the stimuli. Small correlations (between 0.01 and 0.05) are italicized and moderate correlations (between 0.05 and 0.14) are in bold.

Vowel position	Acoustic cue type	Acoustic cue	CI group	CI/CS- group	CS/CS+ group	TH group
1	**Frequency**	**F1 (Hz)**	0.002	0.002	0.002	0.008
		F2 (Hz)	*0.013*	*0.022*	0.006	0.002
		F3 (Hz)	0.005	0.001	*0.011*	0.002
		F1F2 (Hz)	0.004	*0.021*	0.006	0.005
	Bandwidth	**bF1 (Hz)**	0.006	0.008	0.005	0.000
		bF2 (Hz)	0.000	*0.011*	0.007	0.003
		bF3 (Hz)	*0.013*	*0.033*	0.002	0.000
	Amplitude	**aF1 (dB)**	0.005	0.004	*0.044*	0.003
		aF2 (dB)	*0.019*	*0.026*	*0.015*	0.001
		aF3 (dB)	0.001	0.000	0.003	0.001
	Nasal poles detection	**A1-P0 (dB)**	0.000	0.002	0.002	0.007
		A1-P1 (dB)	*0.014*	*0.015*	*0.015*	0.001
	Overall vowel intensity (dB)		*0.011*	0.009	*0.013*	0.000
	Enveloppe difference index		0.006	0.001	*0.040*	0.009
2	**Frequency**	**F1 (Hz)**	0.001	0.004	*0.017*	0.002
		F2 (Hz)	0.001	*0.019*	0.008	*0.016*
		F3 (Hz)	0.008	*0.017*	0.002	0.000
		F1F2 (Hz)	0.001	*0.016*	0.004	0.005
	Bandwidth	**bF1 (Hz)**	0.003	*0.021*	0.001	0.000
		bF2 (Hz)	*0.015*	*0.032*	0.005	0.000
		bF3 (Hz)	0.001	*0.037*	*0.022*	0.001
	Amplitude	**aF1 (dB)**	0.005	*0.031*	0.001	0.000
		aF2 (dB)	*0.011*	*0.037*	0.000	0.006
		aF3 (dB)	0.001	*0.014*	0.004	0.000
	Nasal poles detection	**A1-P0 (dB)**	0.003	0.006	0.000	0.000
		A1-P1 (dB)	0.006	*0.025*	0.000	0.008
	Overall vowel intensity (dB)		0.004	*0.033*	0.003	0.001
	Enveloppe difference index		0.009	0.002	**0.060**	0.001
Overall stimuli temporal enveloppe (dB)			0.000	*0.020*	*0.015*	*0.012*

Appendix 8

Study 6 - Chapter 7: Correlations between the different variables of the factorial model and the first three extracted dimensions.

Variable	Dim.1	Dim.2	Dim.3
NAF_phono	0,483	0,599	-0,384
NAF_phone	0,439	0,688	-0,311
F123_phono	-0,007	0,668	0,302
F123_phone	-0,273	0,586	0,478
SWPM_tot	0,661	-0,027	0,401
SWPM_nas_or	0,730	0,013	0,371
LevelD	0,131	-0,060	0,822
AmpDiff	0,243	-0,060	0,458
SP_1_2	-0,176	0,146	0,177
SP_2_3	0,509	0,244	-0,360
VOT_UV_V	0,346	-0,224	-0,150
PCP	0,801	0,062	-0,058
Naming	0,802	0,142	0,202
VOCD	0,616	-0,281	-0,031
MLUm	0,797	-0,148	0,191
Simple_past	0,626	-0,210	-0,108
Refl_pro	0,458	-0,465	-0,118
Det_del_1syll	-0,639	-0,033	0,108
Det_del_2syll	-0,751	-0,045	0,123