Nasal/oral vowel perception in French-speaking children with cochlear implants and children with typical hearing.

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Abstract

Purpose: The present study investigates the perception of vowel nasality in French-speaking children with cochlear implants (CI group) and children with typical hearing (TH group) aged 4 to 12 years. By investigating the vocalic nasality feature in French, the study aims to document more broadly the effects of the acoustic limitations of cochlear implant 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 cochlear implants (CI group) and 25 children with typical hearing (TH group) divided into three age groups (4-6y., 7-9y. and 10-12y.). 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, 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, but also 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 implanted children, selective use of certain acoustic features, presumed to be better transmitted by the implant, leads to better perceptual performance.

Conclusion: The study's results reveal specific challenges in children with cochlear implants 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.

Keywords: Cochlear implant, vocalic nasality, phonetics, perception, speech development

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 (Fan et al., 2023; Mertens et al., 2022; Canfarotta et al., 2021). 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 (Jahn et al., 2022; DiNino & Arenberg, 2018; Horn et al., 2017). Conversely, children with cochlear implants often exhibit lower performance in spectral resolution (Henry, 2003), and their performance doesn't consistently correlate with age or auditory experience with the implant (Landsberger et al., 2018; DiNino & Arenberg, 2018; Horn et al., 2017). 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 (Grandon et al., 2017; Bouton et al., 2012; Medina & Serniclaes, 2009; Pisoni et al., 1999). Some authors (Bouton et al. 2012; Peng et al., 2019; Cheng, 2020) 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 (Moon and Hong, 2014; Peng, 2019; Cheng, 2020). 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 in French: 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 (Fougeron & Smith, 1993; Borel, 2015). 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; Montagu, 2007; Maeda, 1993) 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 [ɔ̧̃], [ɛ̃] to [ɐ̃], and [ɔ̃] to [õ̧].

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, 1958) 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 (2002, 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 (Kral et al., 2019; Sharma et al., 2020; Gao et al., 2021). 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 (Van Bogaert et al., 2023; Leybaert et al., 2016, 2010 ; Bouton et al., 2011) and speech production (Machart, 2020).

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 (Sharma et al., 2020; Caselli, 2013; Zeitler et al., 2008; Sarant et al., 2014; Anand, 2022) even in noise (Dunn, 2010; Müller, 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:

1) 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.
2) 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, Karltopp 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 1.

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). The TH children were grouped only on their chronological age.

2.2. Stimuli

2.2.1. Stimuli construction

The stimuli consisted of $C_1V_1C_2V_2$ pseudowords where C_1=C_2=/t/ and V_1=V_2= /ɑ̃, ɔ̃, ɛ̃, a, ɔ, ɛ, u/. The phonological and phonetic correspondences for each nasal are reported in Table 3. 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 [tɔ̝tɔ̝] 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 (V_1: 100 ms; V_2: 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 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).

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 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 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 4. The Mann-Whitney tests comparing the phonetic and phonological pairs on the various differential parameters reported in table 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.

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 /tãtã/ near the bus" or "Near the bus, I saw /tãtã/"), 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 6). 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). 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 & Weiseberg, 2019) 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, 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-Sachar 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, 2023).

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 7. 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 ($\beta = 2.052$, SE = 1.0366, $z = 1.98$, $p = 0.0478$) and from ages 4-6 to 10-12 ($\beta = 3.3185$, 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%; $\beta = 1.02$, SE = 0.307, $z = 3.342$, $p < .001$) for both oral ($\beta = -1.15$, SE = 0.401, $z = -2.857$, $p = .004$) and nasal vowels ($\beta = -0.904$, 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/ ($\chi2(1) = 2.9$; $p = .08$). 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%; $\beta = 2.05$, SE = 0.788, $z = -2.6$, $p = .009$), with significant differences for the phoneme /a/ ($\beta = -2.885$, SE = 0.956, $z = -3.016$, $p = .007$) (see Figure 1). The model including the effect of early implantation (without interaction with vowel type) was the second best-fitting model for the CI group (Table 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, $z = 2.589$, $p = .009$).

3.1.2. Identification errors analysis

The confusion matrix (Table 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%.

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 10). Children in the CI group substitute more nasal vowels with phonetically related orals than TH children ($\chi2$ (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 ($\chi2$ (1) = 0.638 ; p =.424).

3.2. Discrimination

In the discrimination task, we analyzed the *d'* scores, which ranged from 0 to 4.65 (see Table 11). 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 12).

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%) ($\chi 2$ = 6.3; p = .012). However, this proportion was statistically equivalent for phonetic pairs (TH = 17.3%, CI = 28.2%; $\chi 2$ = 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.

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).

3.4. 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 oro-pharyngeal 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 (Delvaux, 2012; Delattre, 1968), 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 oro-pharyngeal 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, 2010; Müller, 2002), and in experimental situations (Caselli, 2013; Zeitler et al., 2008; Sarant et al., 2014; Anand, 2022). 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 (Tamati, 2022, Karltopp, 2020; Dettman, 2016).

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 (Jahn et al., 2022 ; DiNino et al., 2018 ; Horn et al. 2017). 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 postlingually deaf adults. The children in our study, who have congenital deafness and were implanted very early, exhibited superior performance. As suggested by Landsberger (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 (Van Bogaert et al., 2023; Leybaert et al., 2016, 2010; Bouton et al., 2011), 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.

6. Data availability statement

The datasets are available from the corresponding author on reasonable request.

7. References

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8. Tables and figures

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	4-6 y.	4-6 y.	12	> 10 m.	Occasionnal
CI2	M	5;10	4-6 y.	4-6 y.	9	≤ 10 m.	Early & frequent
CI3	M	6;8	4-6 y.	4-6 y.	10	≤ 10 m.	Early & frequent
CI4	F	6;10	4-6 y.	4-6 y.	13	> 10 m.	Early & frequent
CI5	M	6;11	4-6 y.	4-6 y.	10	≤ 10 m.	Early & frequent
CI6	F	8;6	8-9 y.	4-6 y.	19	> 10 m.	Occasionnal
CI7	F	8;8	8-9 y.	8-9 y.	12	> 10 m.	Early & frequent
CI8	M	9;7	8-9 y.	8-9 y.	9	≤ 10 m.	Occasionnal
CI9	F	10;8	10-12 y.	8-9 y.	19	> 10 m.	Occasionnal
CI10	M	10;8	10-12 y.	8-9 y.	10	≤ 10 m.	Occasionnal
CI11	M	10;11	10-12 y.	10-12 y.	10	≤ 10 m.	Occasionnal
CI12	F	11;5	10-12 y.	10-12 y.	12	> 10 m.	Early & frequent
CI13	F	11;6	10-12 y.	10-12 y.	30	> 10 m.	Early & frequent

Table 1: Characteristics of the CI children.

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

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

Table 3: Nasal targets and their corresponding oral phonological and phonetic counterparts.

	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	1891	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 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.

	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 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.

	ã		ɛ̃		ɔ̃	
	Pairs	**N**	**Pairs**	**N**	**Pairs**	**N**
phonological pairing	Different :/tãtã/ – /tata/	5	Different : /tɛ̃tɛ̃/ – /tɛtɛ/	5	Different : /tɔ̃tɔ̃/ – /tɔtɔ/	5
	Same : /tãtã/ – /tãtã/	1	Same : /tɛ̃tɛ̃/ – /tɛ̃tɛ̃/	1	Same : /tɔ̃tɔ̃/ – /tɔ̃tɔ̃/	1
	Same : /tata/ – /tata/	1	Same : /tɛtɛ/ – /tɛtɛ/	1	Same : /tɔtɔ/ – /tɔtɔ/	1
phonetic pairing	Different : /tãtã/ – /tɔtɔ/	5	Different : /tɛ̃tɛ̃/ – /tata/	5	Different : /tɔ̃tɔ̃/ – /tutu/	5
	Same : /tãtã/ – /tãtã/	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 6 : Pairs of stimuli in the discrimination task.

		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 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.

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 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.

Stimulus		**Response**						
		ã	**ɔ̃**	**ɛ̃**	**a**	**ɔ**	**u**	**ɛ**
	ã	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 9: Confusion matrix for each target phoneme, for TH and CI groups.

Substitution type	TH	CI	χ2 ; p-value
Nasal ↔ Oral - phonological pairing	5 (0,4%)	4 (0,5%)	χ^2 (1) = 0,638 ; p =.424
Nasal ↔ Oral - phonetic pairing	6 (0,4%)	22 (3%)	χ^2 (1) = 27.2 ; p<.001***

Table 10: Number of substitutions (and % of total number of responses) for each substitution type in TH and CI groups, with associated statistical test.

		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 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.

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

*Figure 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).*

Figure 2: d' scores distribution (mean and 95% CL) for both groups (CI and TH) and pair type (phonological vs phonetic).