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Producing Nasal Vowels Without Nasalization? Perceptual Judgments and Acoustic Measurements of Nasal/Oral Vowels Produced by Children With Cochlear Implants and Typically Hearing Peers

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ABSTRACT

Purpose: The objective of the present study is to investigate nasal and oral vowel production in French-speaking children with cochlear implants (CIs) and children with typical hearing (TH). Vowel nasality relies primarily on acoustic cues that may be less effectively transmitted by the implant. The study investigates how children with CIs 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 consonant-vowel-consonant-vowel–type pseudoword, the vowel being a nasal or oral vowel from French. Thirteen children with CIs and 25 children with TH completed the task. Among the children with CIs, 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 judgments realized on the children's speech productions indicate that children with sustained exposure to CS (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 (a) a benefit of sustained CS practice for CI children for the intelligibility of nasal–oral segments, (b) privileged exploitation of temporal (segmental duration) and salient acoustic cues (oropharyngeal configuration) in the CS+ group, and (c) difficulties among children with CI in distinguishing nasal–oral segments through nasal resonance.
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In prelingually deafened children with cochlear implants (CIs), specific characteristics in productive skills have already been observed in numerous studies. For oral vowels, children with CIs differed from typically hearing peers in F1 and F2 frequency values and showed a

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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 (TH), 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 & Vilain, 2020). In the production of vowels, differences have been observed between French-speaking children with CIs and those with 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; 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 (Cheng & Chen, 2020; Eshaghi et al., 2022; Peng et al., 2019). This article will specifically focus on a phonological feature carried by fine acoustic cues and therefore likely to be problematic for CI users, namely, the vowel nasality feature in French.

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 is not 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. The 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 morphophonological alternations in French grammar are supported by this contrast.

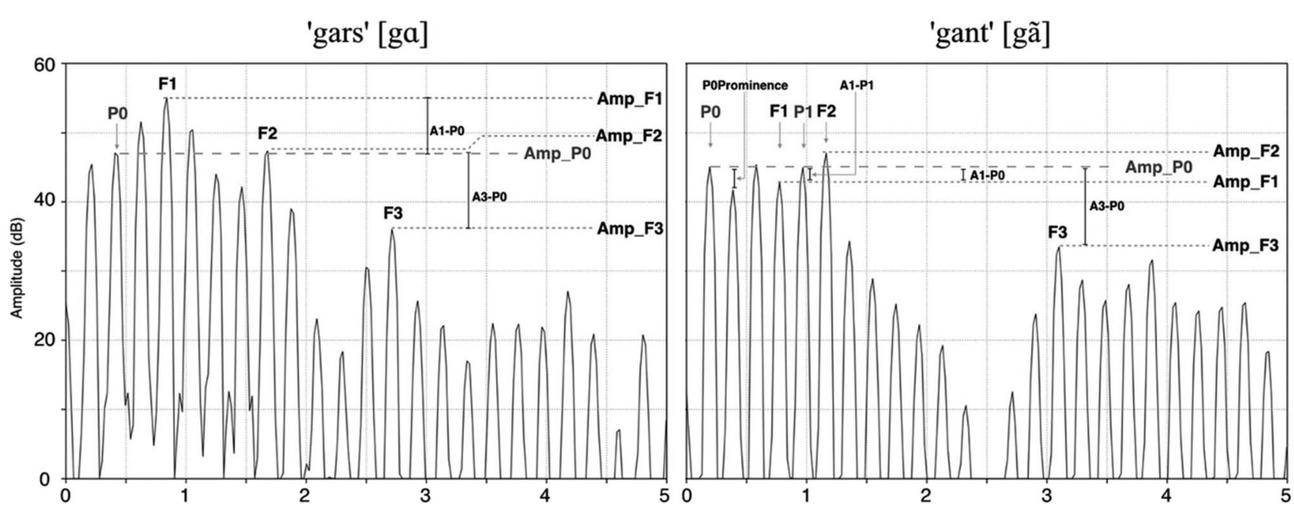
The adequate production of a nasal vowel requires a combination of two elements: (a) adopting an oropharyngeal configuration inherent to a specific vowel quality and (b) adding nasal resonance through the opening of the soft palate. At the suprasegmental level, a lengthening of the duration of nasal vowels has been reported (Delattre, 1954; Delattre & Monnot, 1968), and segmental lengthening has also been shown to correlate with listeners' perception of nasality (Delvaux, 2021).

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 differ not only 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 (VP) 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, 2021). Several authors have identified measurable spectral changes related to vocalic nasality, such as 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 and colleagues (Delvaux, 2002; Delvaux & Metens, 2002) suggest 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. M. Y. 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, that is, "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 and 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 (see Figure 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 intersubject variability of the measurements, demonstrating that the acoustic manifestations of nasality were speaker and language specific.

In view of the difficulty of identifying a single metric for nasalization that is sufficiently precise and robust, Carignan (2021) proposed a new system for quantifying the time-varying degree of nasalization. The method, called NAF (for "Nasalization from Acoustic Features"), consists, for each speaker, of a model of how nasal and

Figure 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 is from the study of Styler (2017). Reprinted with permission from Styler, W. (2017). On the acoustical features of vowel nasality in English and French. *The Journal of the Acoustical Society of America, 142*(4), 2469–2482. Copyright © 2017, Acoustical Society of America.



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.

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 CIs 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 depends more on temporal envelope cues, was better processed. Borel and colleagues' (Borel, 2015; Borel et al., 2019) research investigated the perception skills of 82 French-speaking adults with unilateral CIs. 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 1 year of implant use. The authors 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, that is, in terms of formant values (reflecting the oropharyngeal configuration), according to the literature (Carignan, 2014; Maeda, 1993; Montagu, 2007); these pairings are also 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 TH, 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., 2024), 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[1] (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.

[1]Cued Speech is a rehabilitation method for individuals with hearing impairments. Manual cues are added to spoken language to provide a visual clue that complements lipreading, making all phonological contrasts of a spoken language visually accessible.

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.

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 (M. Y. Chen, 1995), and nasalance measurements (Fletcher et al., 1999). The most direct explanation for this phenomenon would be that the closure of the VP is not properly accomplished (absent, incomplete, or not maintained) due to inadequate auditory feedback. Lock and Seaver (1984) proposed that perceived hypernasality might be associated not only 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- versus post-implantation performances (L. H. P. Nguyen et al., 2008) or with implant turned on versus off (Svirsky et al., 1998). More recently, Baudonck et al. (2015) studied nasality in 36 Flemish-speaking deaf children with CIs, comparing them to 26 typically hearing children and 25 deaf children with conventional hearing aids (HAs), 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 recipient children.

To our knowledge, no study has investigated the production of the nasal contrast for French vowels in CI 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.

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: (a) cues associated with oropharyngeal configuration (F1, F2, F3), (b) cues associated with velopharyngeal coupling (using the NAF method), and (c) 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 CS aims to create a complete and stable phonological system by providing visual cues (hand shapes and positions) to lipreading, 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 & LaSasso, 2010; Van Bogaert et al., 2023), including the perception of vocalic nasality (Fagniart et al., 2024). 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 (Machart, 2022; Machart et al., 2021). In this perspective, the performances of children with TH 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 and (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. Second, 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 CI recipients, it is hypothesized that children will exhibit distinct productive profiles according to their auditory status. More precisely, it is expected that children with CIs, compared to children with TH, differentiate between oral and nasal vowels

   (a) by using more segmental lengthening (as evidenced by vowel durations),

   (b) based more on differences in oropharyngeal configuration (as evidenced by formant values), and

   (c) by making less use of the cues associated with velopharyngeal 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.

Method

Participants

The study was conducted on the same participants as reported in a previous study (Fagniart et al., 2024): a group of prelingually deafened children with bilateral CIs (CI group) and a control group of children with TH (TH group). The CI group consisted of 13 children (seven girls and six boys), aged between 5;8 (years;months) and 11;6 (M = 8;7 ± 2;4), 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 (M = 13;7 ± 6 months). 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. This group was divided based on their level of CS exposure: Six 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 seven 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 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 1.

The TH group comprised 25 children, with 11 girls and 14 boys, ranging in age from 5 to 12 years (M = 8;6 ± 2;4). 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 with CIs were recruited. Informed consent was obtained from the parents or legal guardians of all children.

Data Collection

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., 2024). The target pseudowords were in the form of $C^1V^1C^2V^2$ where $C^1 = C^2$ = /t/ and $V^1 = V^2$ = /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 2. The constructed stimuli were thus /tɑ̃tɑ̃/, /tɔ̃tɔ̃/, /tɛ̃tɛ̃/, /tata/, /tɔtɔ/, /tɛtɛ/, and /tutu/.

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,

Table 1. Characteristics of the CI group.

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	Occasional
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	Occasional
CI7	F	8;8	12	25	Early & frequent
CI8	M	9;7	9	51	Occasional
CI9	F	10;8	19	NA	Occasional
CI10	M	10;8	10	NA	Occasional
CI11	M	10;11	10	29	Occasional
CI12	F	11;5	12	33	Early & frequent
CI13	F	11;6	30	43	Early & frequent

Note. CI = cochlear implant; M = male; F = female; NA = not available.

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 25 cm from the child.

During the assessments, some children did not complete the task for various reasons, such as fatigue. Out of the 1,064 sentences expected (28 × 38 participants), 27 were missing, which accounts for 2.5% of the expected number of produced sentences. As a result, 1,037 sentences were collected, totaling 2,074 registered vowels. The productions of the children were manually segmented and annotated using the Praat software (Boersma & Weenink, 2023) to isolate the 2,074 vowels.

Table 2. Nasal targets and their phonological and phonetic counterparts.

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

Analysis of the Speech Productions

Perceptual Judgments

All the vowels produced by the children were used in judgment 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 interjudge 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, that is, all the vowels produced by five to six children (from both TH and CI groups). Additionally, the 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: (a) 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 (b) 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 α coefficient of .931. Their agreement on the forced-choice identification task of productions from the same participant is more moderate, with a Fleiss κ of .41. Agreement between the eight raters and the first author was also measured on the entire set of production (2,074 productions), with Cronbach's α equal to .801 (good agreement) for the nasality task and Cohen's κ of .497 (moderate agreement) for the forced-choice identification task.

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. First, 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 ±3 *SD*s 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 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 11 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 (2021) (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 (2021; Carignan et al., 2023), such as formant frequency values and the first nine Mel-frequency spectral coefficients, which show moderate correlations with formant values, were not included here. Obtaining predicted nasality values using Carignan's method (2021, Carignan et al., 2023) 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 time points from the most stable part of the vowel, excluding points at 0%, 10%, 90%, and 100% of the total vowel duration. Then, we extracted time points 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 time points at 30%, 50%, and 70% 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; T. Chen & Guestrin, 2016) with linear regression outcomes was realized. In order to optimize the model, the values of four hyperparameters (max_depth, eta, gamma, and subsample) were tuned using a fivefold 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 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 13,844 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 ($F1_1$, $F2_1$, $F3_1$) for the three first formants in Hz, and V2, an oral vowel with coordinates ($F1_2$, $F2_2$, $F3_2$), the Euclidean distance d between these vowel points is given by

$$d_{v1v2} = \sqrt{\left((F1_{v2} - F1_{v1})^2 + (F2_{v2} - F2_{v1})^2 + (F3_{v2} - F3_{v1})^2\right)} \quad (1)$$

- Differences between segmental duration values
- Differences between NAF values

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/, /ɛ/−/a/), and the interaction between these variables. To account for intersubject 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 models 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.

Results

Table 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 Supplemental Material S1.

Perceptual Judgments on Speech Productions

Nasality Judgment Ratings

Analysis of the nasality judgment ratings showed no significant effect of auditory status (CI: 4.46, TH: 4.57; $\beta = 0.05$; $SE = 0.2$; $t = 0.28$; $p = .78$) or 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−, CS+, and 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

Table 3. Mean values of the different dependent variables (perceptual judgments and acoustic measures) by vowel and vowel type among the different groups.

Measure	Vowel/ vowel type	Values				Test *p* values			
		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	*NS*	*NS*	*NS*	*NS*
	ɔ̃	7.13	6.6	7.6	7.1	*NS*	*	*NS*	*NS*
	ɛ̃	6.72	5.6	7.7	6.9	*NS*	***	***	*
	a	2.11	2.4	1.8	2.3	*NS*	*NS*	*NS*	*NS*
	ɛ	1.88	2.0	1.8	2.0	*NS*	*NS*	*NS*	*NS*
	o	2.74	3.0	2.5	2.8	*NS*	*NS*	*NS*	*NS*
	u	3.12	3.3	3.0	3.4	*NS*	*NS*	*NS*	*NS*
	Nasal	7.13	6.5	7.7	7.2	*NS*	***	*	*NS*
	Oral	2.49	2.7	2.3	2.6	*NS*	*NS*	*NS*	*NS*
Duration (ms)	ɑ̃	143	142	144	126	*	*NS*	*NS*	*NS*
	ɔ̃	145	145	145	129	.06	*NS*	*NS*	*NS*
	ɛ̃	147	141	154	133	.07	.06	*NS*	*NS*
	a	98	98	99	96	*NS*	*NS*	*NS*	*NS*
	ɛ	102	108	98	91	*NS*	*NS*	*NS*	*NS*
	o	109	117	103	95	.09	*NS*	*NS*	*NS*
	u	107	112	103	89	*	*NS*	*NS*	*NS*
	Nasal	145.8	143	148	129	*	*NS*	*NS*	*NS*
	Oral	104.6	109	101	93.3	*NS*	*NS*	*NS*	*NS*
F1 (Hz)	ɑ̃	495	523	472	502	*NS*	*	*NS*	*
	ɔ̃	423	415	429	428	*NS*	*NS*	*NS*	*NS*
	ɛ̃	507	568	455	502	*NS*	***	***	***
	a	679	641	713	642	*NS*	*	*NS*	*
	ɛ	530	490	564	529	*NS*	***	***	*NS*
	o	463	460	464	451	*NS*	*NS*	*NS*	*NS*
	u	402	388	415	388	*NS*	*NS*	*NS*	*
	Nasal	475	503	450	477	*NS*	***	*NS*	**
	Oral	519	495	539	501	*NS*	**	*NS*	*
F2 (Hz)	ɑ̃	1124	1072	1166	1251	**	*NS*	**	*NS*
	ɔ̃	1181	1653	1375	1205	*NS*	**	*NS*	*NS*
	ɛ̃	1505	1087	1261	1424	***	***	***	*NS*
	a	1835	1729	1927	1883	*NS*	*	*	*NS*
	ɛ	2477	2373	2568	2383	*NS*	*NS*	*NS*	*NS*
	o	1327	1327	1331	1385	.07	*NS*	*NS*	*NS*
	u	1239	1252	1227	1210	*NS*	*NS*	*NS*	*NS*
	Nasal	1271	1275	1269	1293	*NS*	*NS*	*NS*	*NS*
	Oral	1717	1670	1757	1714	*NS*	*NS*	*NS*	*NS*
F3 (Hz)	ɑ̃	2533	2732	2365	2595	**	***	*NS*	***
	ɔ̃	2620	2672	2574	2453	*NS*	*NS*	*NS*	*NS*
	ɛ̃	2863	2958	2782	2909	***	*NS*	*NS*	***
	a	3492	3432	3548	3502	*NS*	*NS*	*NS*	*NS*
	ɛ	3549	3397	3683	3603	*NS*	*	*	*NS*
	o	2957	2914	2989	2832	.06	*NS*	*NS*	*NS*
	u	2668	2605	2726	2317	***	*	*NS*	***
	Nasal	2671	2790	2568	2651	*	*	*NS*	**
	Oral	3166	3087	3235	3061	*	*NS*	*NS*	*
NAF	ɑ̃	0.73	0.76	0.71	0.77	*NS*	*NS*	*NS*	*NS*
	ɔ̃	0.53	0.56	0.50	0.59	*	*NS*	*NS*	*
	ɛ̃	0.62	0.49	0.74	0.75	***	***	***	*NS*

(*table continues*)

Table 3. *(Continued).*

Measure	Vowel/ vowel type	Values				Test *p* values			
		CI	CS−	CS+	TH	CI/TH	CS−/CS+	CS−/TH	CS+/TH
	a	0.43	0.40	0.45	0.30	***	*NS*	**	***
	ε	0.14	0.13	0.15	0.11	*NS*	*NS*	*NS*	*NS*
	o	0.31	0.30	0.32	0.24	**	*NS*	*NS*	*
	u	0.39	0.42	0.37	0.30	***	*NS*	**	*
	Nasal	0.63	0.61	0.65	0.70	***	*NS*	**	*NS*
	Oral	0.32	0.31	0.32	0.23	***	*NS*	**	**

Note. 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. CI = cochlear implant; CS = Cued Speech; TH = typical hearing; NS = not significant; NAF = Nasalization from Acoustic Features.

same vowel /ɛ̃/ compared to the CS+ group (β = −0.83; *SE* = 0.32; *t* = −2.59; *p* = .02).

Figure 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 vowels produced by children in 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.

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 CS 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+ groups. It is important to note that the various effects were only moderate (57.5%–62%) in terms of statistical power (see Supplemental Material S1) and should therefore be interpreted with caution.

Table 4 shows the identification matrix of the judges' identification responses across the three groups of children (TH, CI/CS+, and CI/CS−), allowing to

Figure 2. Density plot of the nasality judgment score distribution among the CI/CS− (red and solid line), CI/CS+ (green and dashed line), and TH (blue and long dashed line) groups. CI = cochlear implant; CS = Cued Speech; TH = typical hearing.

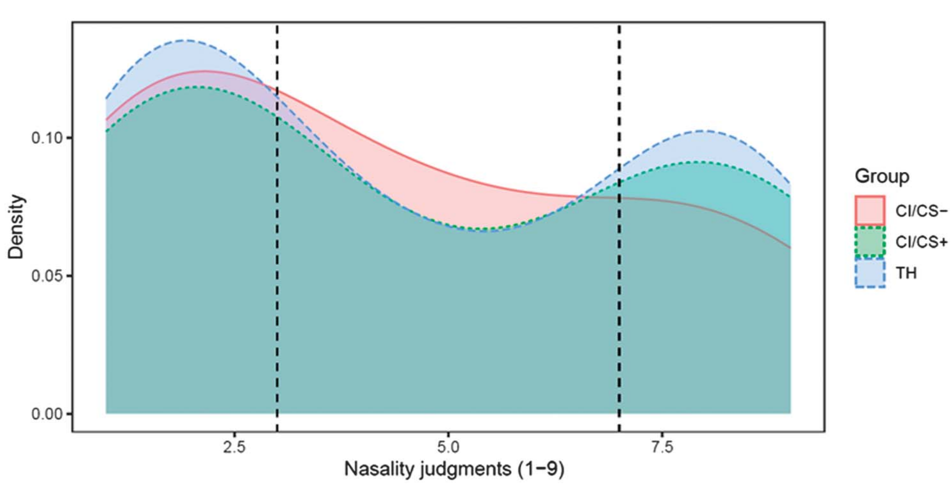
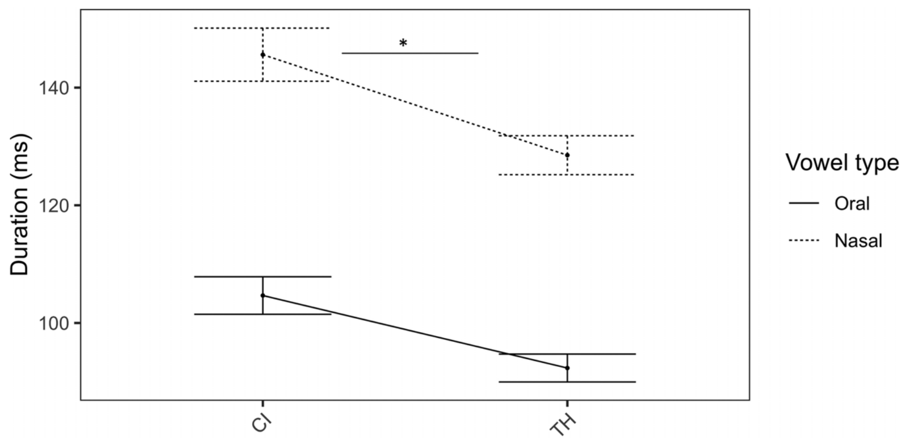


Table 4. Identification matrix of the judge's identification percentages among the CI/CS−, CI/CS+, and TH groups.

Vowel			Identified vowel												
			ɑ̃	**ɔ̃**	**ɛ̃**	**a**	**o**	**ɛ**	**u**	**ɔ**	**e**	**œ**	**ə**	**ø**	**y**
Target vowel	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

Note. Correctly identified productions are represented in diagonal and bold typology. CI = cochlear implant; CS = Cued Speech; TH = typical hearing.

Figure 3. Mean and standard deviation (error bars) of duration values (ms) 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 (*). CI = cochlear implant; TH = typical hearing.



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/, and /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 were a substantial proportion of substitutions between a nasal vowel and its phonetic counterpart that 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.

Acoustic Measurements on Speech Productions

Segmental Duration Values

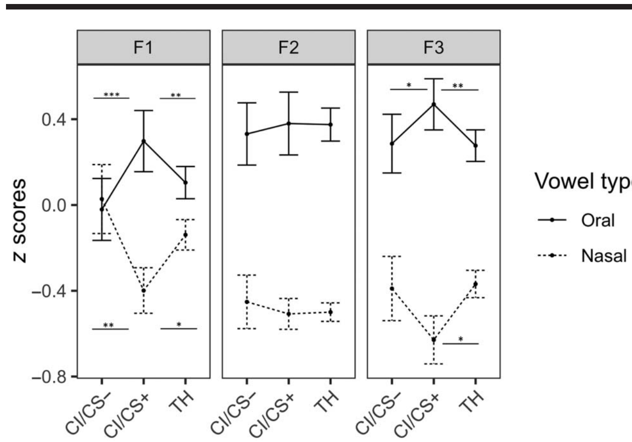
A significant effect of auditory status was observed on the segmental durations, with the CI group displaying overall longer segmental values (CI: 122, TH: 108; β = −16.25; *SE* = 7.77; *t* = −2.09; *p* = .04, moderate effect size of 52%), with an interaction with vowel type at the borderline of significance ($\chi^2(1)$ = 3.12; *p* = .07). Figure 3 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).

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.

Formant Values

The F1 values did not show an effect of auditory status (β = 0.06; *SE* = 0.07; *t* = −0.91; *p* = .36) or an interaction with vowel type. Figure 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 ($\chi^2(2)$ =

Figure 4. Mean and standard deviation (error bars) of F1, F2, and F3 frequency values converted into *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 (***). CI = cochlear implant; CS = Cued Speech; TH = typical hearing.



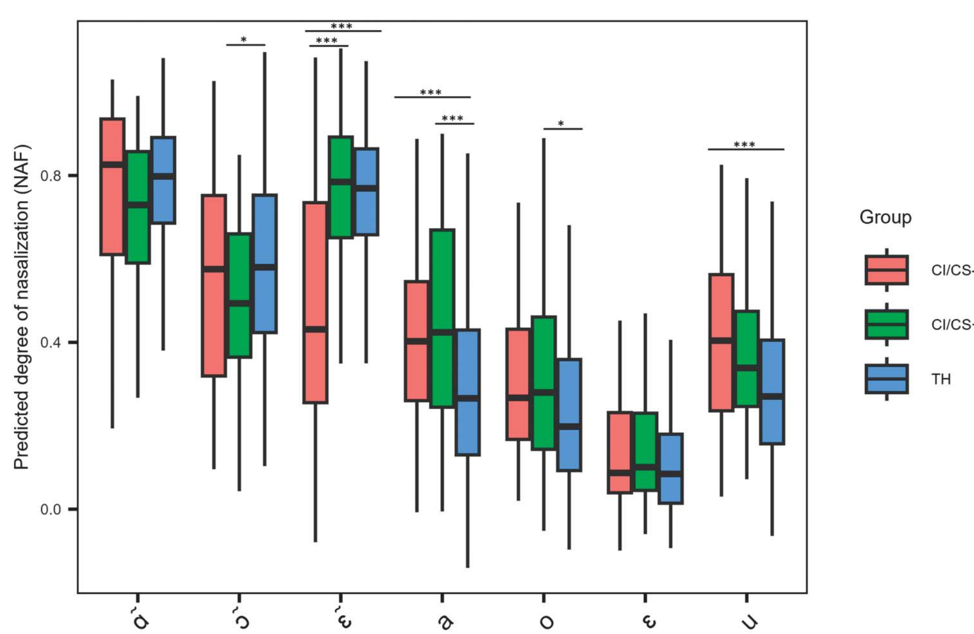
26.88; $p < .001$). Indeed, F1 values were significantly lower in the CI/CS+ group for nasal vowels and higher for oral vowels compared to the other two groups. This effect was significant for nasal vowels /ɑ̃/ and /ɛ̃/, as well as oral vowels /a/ and /u/. Vowel /ɛ/ exhibited significantly lower values 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. In summary, as displayed in Figure 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.

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 vowels /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 the CI/CS− group ($\beta = -0.09$; $t = -3.53$; $p < .001$), but lower values for the oral vowels than the CI/CS+ group ($\beta = 0.09$; $t = 3.9$; $p = .001$) and CI/CS− group ($\beta = 0.08$; $t = 3.2$; $p = .006$). Figure 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

Figure 5. Box plots of NAF values among the CI and TH groups for the target vowels. Significance levels for pairwise comparison tests are shown when the difference is significant at .05 (*) or < .001 (***). CI = cochlear implant; CS = Cued Speech; NAF = Nasalization from Acoustic Features; TH = typical hearing.



TH group for /ɛ̃/ and higher than the CI/CS− group. The TH group showed significantly lower NAF values for the oral vowel /a/ than the CI/CS− and CI/CS+ groups, lower than the CI/CS+ group for /o/, and lower than the CI/CS− group for /u/.

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, that is, one of the six pairs (see Table 2; $\chi^2(5) = 73.78$; $p < .001$), indicating larger differences in duration within the /ɑ̃/−/a/ ($\beta = 15.42$; $z = 2.68$; $p = .007$) and /ɛ̃/−/a/ ($\beta = 13.1$; $z = 2.28$; $p = .02$) 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 ($\chi^2(5) = 61.02$; $p < .001$). 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 ($\beta = 0.17$; $SE = 0.04$; $z = 3.6$; $p < .001$) 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 6. Box plots of delta durations, F1/F2/F3 EDs, 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 (***). CI = cochlear implant; CS = Cued Speech; ED = Euclidean distance; NAF = Nasalization from Acoustic Features; TH = typical hearing.

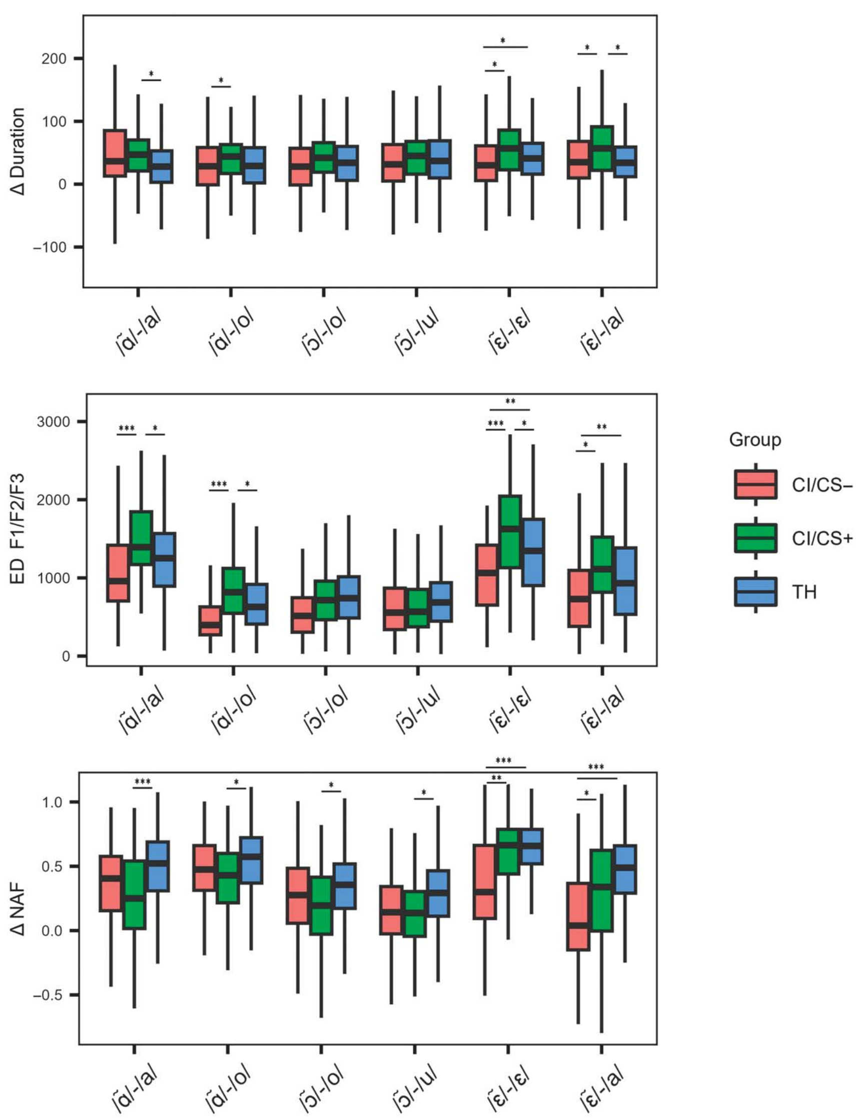


Figure 6 illustrates the pairwise comparisons across the TH, CI/CS+, and CI/CS− groups for the three types of acoustic cues. For duration values, an interaction effect was observed between the CS exposure grouping and pair type ($\chi^2(10) = 104.47$; $p < .001$). Indeed, differences in duration are greater in the CS+ group than in the TH group for the /ɑ̃/−/a/ ($\beta = 16.28$; $z = 2.29$; $p = .05$) and /ɛ̃/−/a/ ($\beta = 19.37$; $z = 2.72$; $p = .01$) 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 ($\chi^2(10) = 316.25$; $p < .001$). 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− ($\beta = -0.17$; $z = -2.78$; $p = .01$) and CS+ ($\beta = -0.14$; $z = -2.47$; $p = .03$) groups. Looking more closely at the nasal–oral pairs (as shown in Figure 6), the CI/CS+ group had significantly lower NAF value differences than the TH group for /ɑ̃–a/, /ɑ̃–o/, /ɔ̃–o/, and /ɔ̃–u/, while the CI/CS− group had significantly lower values than the TH and CI/CS+ groups for /ɛ̃–a/ and /ɛ̃–ɛ/.

Relation Between Perceived Nasality and Acoustical Data

Multiple regression modeling was performed in three groups of participants, respectively, in order to uncover the speaker- and task-related variables as well as the acoustic cues that better predict perceived nasality among nasal vowels as measured by the degree of nasality ratings (see Table 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.

Table 5. Results of the multiple regression modeling across the CS−, CS+, and TH groups for nasal vowels predicting perceived nasality in perceptual judgments.

Variable	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^2	.38***	.2***	.08***

Note. Significance levels for each predictive variable are shown when the difference is significant at .05 (*) or < .001 (***). CS = Cued Speech; TH = typical hearing; NA = not available; NAF = Nasalization from Acoustic Features.

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, 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 versus 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., 2024, and previously described by Borel, 2015).

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 simple effect of auditory status was observed on the percentage of vowel identification. It was only by considering the exposure of children with CIs 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 (Leybaert & LaSasso, 2010; 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 nonecological 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; N. Nguyen & Fagyal, 2008), which is usually disambiguated in ecological situations through lipreading 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.

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 the degree of phonetic nasalization. Regarding duration cues, it had been hypothesized that children with CIs 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 that the vowels produced by the CI/CS+ group were better perceived overall. Given that temporal cues are well coded by the CI, it is probably not surprising that segmental duration is favored by children with CIs to implement the oral–nasal contrast in their vowel productions. In a previous study (Fagniart et al., 2024), 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, in both 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 CIs, 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 lipreading 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 (2022) 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 and colleagues (Carignan, 2021; Carignan et al., 2023). Given the limitations of CIs in precisely transmitting spectral resolution (Jahn et al., 2022), these acoustic cues associated with VP opening may be more challenging for children with CIs 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 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. suggested possible difficulties in the control of the VP 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., 2024). If the partially complete auditory input transmitted by the CI 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 CIs. A prior study demonstrated the positive impact of CS in the identification and discrimination of nasal and oral vowels (Fagniart et al., 2024). 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 lipreading, aims to enable complete differentiation of all the sounds in the language using visual cues. The auditory input from the CI, combined with intensive use of CS, seems to have allowed children in the CS+ group to better distinguish nasal and oral vocalic segments, in both 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 CIs 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 CI 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" (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 lipreading) 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.

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 modeling 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 VP 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.

Contributions and Limitations of the Study

This study has provided valuable initial results on the productive skills of children with CIs 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 participants. 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 postlingually 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.

Conclusions

The results of the study highlight (a) a benefit of sustained CS practice in children with CI for the intelligibility of their oral and nasal vowels; (b) a privileged exploitation of the acoustic characteristics associated with visually salient cues in the CS+ group, that is, acoustic cues dependent on the oropharyngeal configuration of the vowel (in particular, tongue height and lip rounding); and (c) difficulties among children with CI in distinguishing nasal–oral vowels on the basis of phonetic nasalization (i.e., nasal resonance resulting from velopharyngeal coupling). These findings shed light on the importance of understanding the mechanisms through which children with CIs 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.

Data Availability Statement

The data sets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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