Link Between Acoustic Production Profiles and Linguistic Performance in Children With Cochlear Implants

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Background. Although early cochlear implantation allows young children with congenital deafness to reach linguistic levels close to those of typically hearing (TH) peers, certain domains remain at risk, particularly phonology and morphosyntax, with substantial variability in performance. One explanatory factor often mentioned is the degraded spectral quality of the auditory signal transmitted through the cochlear implant (CI), which may lead to imprecise phonological representations and, consequently, weaker linguistic skills. However, several studies have shown that some compensatory strategies can mitigate the impact of these perceptual limitations, such as the use of visually accessible cues.

Objectives. This study aimed to examine the relationship between the production profiles of speech sounds that are likely to be poorly encoded through the CI and the linguistic performance of children with CI and their TH peers, to determine whether compensatory strategies for perceptual limitations are associated with better linguistic outcomes.

Methods. Twenty-three children aged from 3 years and 8 months to 7 years and 10 months with congenital deafness using cochlear implants, and a control group of 47 typically hearing children matched for chronological and hearing age, completed picture-naming, narrative production, and morphological processing tasks. Acoustic measurements were extracted for three types of speech segments (nasal/oral vowels, fricatives, and plosives) to characterize production profiles and relate them to linguistic scores reflecting phonological, lexical, and morphosyntactic levels. A principal components analysis followed by hierarchical clustering made it possible to identify distinct performance profiles. Thirteen CI children were reassessed one year later to analyze longitudinal changes in performance.

Results. Three main dimensions were extracted from the PCA: the first, discriminating between groups, was related to linguistic performance, while the second and third accounted for acoustic production profiles. Hierarchical classification revealed four performance clusters: Cluster 1 (CI participants only) included children with the lowest linguistic performance and the least distinctive productions, while Cluster 4 (TH participants only) included those with the best linguistic and acoustic performance. Clusters 2 and 3, composed of participants from both groups, showed intermediate levels of linguistic performance and effective production strategies that compensated for the impact of perceptual difficulties (for example, by exploiting articulatory cues that are more visually accessible). The longitudinal analysis showed overall but heterogeneous improvement, with only four children moving to a cluster associated with higher linguistic performance.

Conclusion. Children in the CI group whose production profiles indicated effective compensation for perceptual limitations achieved better linguistic performance. However, their progress at the one-year follow-up remained variable, suggesting a possible cognitive cost associated with these compensations.

Keywords: cochlear implant, deafness, phonetics, phonology, morphosyntax, factorial analyses

Lien entre les profils de production acoustique et les performances linguistiques d'enfants porteurs d'implants cochléaires

Contexte : Bien que l'implantation cochléaire précoce permette à de jeunes enfants présentant une surdité congénitale d'atteindre des niveaux linguistiques proches de ceux d'enfants entendants, certains domaines restent à risque, notamment les niveaux phonologique et morphosyntaxique, avec une variabilité importante des performances. L'un des facteurs explicatifs évoqués est la dégradation spectrale du signal transmis par l'implant, susceptible d'entraîner des représentations phonologiques imprécises et, par conséquent, des faiblesses linguistiques. Toutefois, plusieurs travaux ont montré que certaines stratégies de compensation (par exemple, exploitation d'indices visuellement accessibles) peuvent limiter l'impact de ces limitations perceptives.

Objectifs : La présente étude visait à examiner les liens entre les profils de production de sons de parole susceptibles d'être mal codés par l'implant cochléaire (IC) et les performances linguistiques d'enfants porteurs d'un IC et d'enfants à audition typique (AT), afin de déterminer si des stratégies de compensation des limites perceptives sont associées à de meilleures performances linguistiques.

Méthodes : Vingt-trois enfants âgés de 3 ans et 8 mois à 7 ans et 10 mois présentant une surdité congénitale et porteurs d'un IC, ainsi qu'un groupe de 47 enfants à audition typique appariés en âge chronologique et auditif, ont participé à des tâches de dénomination, de production narrative et de traitement morphémique. Des mesures acoustiques ont été extraites pour trois types de segments (voyelles nasales/orales, fricatives et occlusives) afin de caractériser les profils productifs et de les relier aux indices linguistiques reflétant les niveaux phonologique, lexical et morphosyntaxique. Des analyses en composantes principales (ACP) suivies de classifications hiérarchiques ascendantes ont permis d'identifier des profils de performance. Treize enfants porteurs d'un IC ont été réévalués un an plus tard pour analyser l'évolution longitudinale de leurs performances.

Résultats : Trois dimensions principales ont été extraites de l'ACP : la première, discriminant les deux groupes, était liée aux performances linguistiques, tandis que les deux suivantes rendaient compte des profils acoustiques de production. La classification a mis en évidence quatre classes de performance : la classe 1 (IC uniquement) regroupait les enfants aux performances linguistiques les plus faibles et aux productions les moins distinctives ; la classe 4 (AT uniquement) correspondait aux meilleures performances et à des productions acoustiquement typiques. Les classes 2 et 3, mixtes, présentaient des niveaux intermédiaires et des stratégies de production efficaces compensant l'impact des difficultés perceptives (exploitation des indices articulatoires visuellement plus accessibles par exemple). L'analyse longitudinale a montré une amélioration générale mais hétérogène, seuls quatre enfants progressant vers une classe associée à un niveau linguistique supérieur.

Conclusion : Les enfants du groupe IC dont les profils de production témoignaient de compensations efficaces face aux limites perceptives ont obtenu de meilleures performances linguistiques. Toutefois, leur progression lors du suivi à un an reste variable, ce qui suggère un possible coût cognitif associé à ces compensations.

Mots-clés : implant cochléaire, surdité, phonétique, phonologie, morphosyntaxe, analyses factorielles

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INTRODUCTION

The language skills of children with cochlear implants (CI) have been extensively studied to determine whether they are able to achieve the same level of language proficiency as their typically hearing (TH) peers. Performance levels vary depending on the language components investigated: lower performance compared to TH children is frequently reported in the phonological (Bouton et al., 2012; Gaul Bouchard et al., 2007) and morphosyntactic domains (Bourdin et al., 2016; Caselli et al., 2012; Duchesne et al., 2010; Le Normand & Thai-Van, 2023), although these results show considerable variability. Lexical development has been more often reported as showing levels of development close to those of TH children (Caselli et al., 2012; Duchesne et al., 2009; Rinaldi et al., 2013). These heterogeneous linguistic performances can be explained, on the one hand, by delayed exposure to spoken language prior to implantation and, on the other hand, by perceptual limitations related to the processing of sound signals through the CI. These perceptual limitations would have a greater impact on speech sounds that rely on fine-grained acoustic cues, such as vowel nasalization (Borel, 2015; Bouton et al., 2012; Fagniart et al., 2024a) or consonant articulation places (Bouton et al., 2012; Cheng & Chen, 2020; Medina et al., 2004; Peng et al., 2019). Speech sounds whose acoustic correlates depend on high frequencies also appear to be vulnerable, as observed for fricative consonants (Grandon, 2016; Mildner et al., 2006; Reidy et al., 2017; Todd et al., 2011; Warner-Czyz & Davis, 2008).

However, despite these perceptual constraints, most children with CI manage to construct phonological representations of these more "vulnerable" speech sounds. The performance of 13 children with CI in tasks involving the identification and discrimination of pseudowords containing nasal and oral vowels was above chance, although below that of their 25 TH children matched on chronological age (Fagniart et al., 2024a). It can be assumed that these children, having constructed their phonological representations from a limited auditory signal, were able to rely more on acoustic cues that are better transmitted by the CI, such as temporal cues or formant frequencies, particularly when these cues are concomitant to visible articulatory movements (rounding of the lips, mouth opening). This can be supported by the observation of links between the children's performance and the use of these more accessible acoustic cues: children with better identification/discrimination performance appear to be those who have benefited most from very slight temporal distances between nasal and oral vowels.

A second study (Fagniart et al., 2025a) investigated the performance of nasal and oral vowel production in the same group of participants, using perceptual analyses (identification of the vowel produced and the degree of nasalization by judges) and acoustic analyses (aimed at studying the formant characteristics of the productions, the degree of nasalization, and the duration of vowels). Children whose productions were best identified by judges were also those who made a greater distinction between nasal and oral vowels using differentiated formant patterns, reflecting distinct oropharyngeal configurations, as well as vowel lengthening of nasal vowels. These production strategies were found in children with intensive and regular exposure to Cued Speech (CS)[1]. Moreover, acoustic analyses reveal significantly less distinction between nasal and oral vowels based on nasal resonance structure in children with CI compared to their hearing peers. This seems to demonstrate the perceptual limitations of children with CI in processing this particularly complex spectral acoustic information (see Fagniart et al., 2025a, for more details on the acoustic characteristics of nasal vowels).

In this context, it is hardly surprising to observe wide variability in linguistic performance: the perceptual limitations of CI make it difficult to perceive certain speech sounds, which has an impact on the quality of phonological representations. However, the development of lexical and morphosyntactic components relies on the memorization and manipulation of precise phonological forms. The greater vulnerability of the morphosyntactic domain compared to the lexical domain, as well as the close links between phonology and morphosyntax in populations with language disorders, have been interpreted as reflecting the low perceptual salience of grammatical elements in the spoken chain (i.e., morphophonology) compared to more salient lexical elements, and a cognitive advantage of lexical elements, which have concrete conceptual content and are easier to teach (Hage, 2005).

1 System of gestural codes accompanying spoken language to provide visual cues that complement lip reading, thus making all the phonological contrasts of a spoken language visually accessible (Charlier, 2020)

These proposals form the basis of phonological theories of morphosyntactic disorders in children with developmental language disorder (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992; Parisse & Maillart, 2008). Convergent results were obtained in a previous study on children with CI (Fagniart et al., 2025b), which revealed specific correlations between phonological and morphosyntactic levels, as well as correlations across all linguistic levels (phonological, lexical, and morphosyntactic) in typically hearing children matched for chronological and hearing age. Given the findings that perceptual limitations can be compensated for by exploiting acoustic cues that are better transmitted by CI in some children, it seems reasonable to ask whether these compensations are associated with better linguistic performance, particularly in terms of morphosyntactic processing and production.

Aims of the study

In this context, this study aims to examine the link between acoustic features of the vulnerable speech sounds in the production of children with CI and their linguistic performance in the phonological, lexical, and morphosyntactic domains. Indeed, the high variability observed among CI users in their ability to process certain vulnerable speech sounds could help explain the variability observed in phonological performance and, consequently, in morphosyntactic skills, the latter being based on precisely specified phonological and lexical representations.

Two groups of children were recruited: a group of children with CI and a group of children with typical hearing, matched according to chronological or auditory age. Perceptual abilities were not directly assessed, but inferred from acoustic analyses of segment productions presenting a wide range of acoustic correlates and varying degrees of difficulty for transmission via the CI. Three categories of segments were therefore selected to explore production indices presenting different degrees of perceptual difficulty via the CI:

- Nasal and oral vowels: their distinction relies on two strategies for producing vowel nasalization, which were analyzed acoustically: (1) the degree of nasal resonance, based on subtle acoustic cues (e.g., the amplitude ratio of the first harmonics), which are particularly vulnerable to processing by cochlear implants; (2) the specific oropharyngeal configuration of the target vowel, analyzed through formant measurements. These acoustic cues are more easily exploitable when formants are clearly distinct and associated with visible articulatory dimensions (e.g., vowel height and lip rounding) (Fagniart et al., 2025a; Fagniart et al., 2024a).

- Fricative consonants: specific difficulties have been reported both in the discrimination of places of articulation (Giezen et al., 2010; Hedrick et al., 2011; Lane et al., 2001; Mildner & Liker, 2008; Reidy et al., 2017) and in the acoustic characteristics of frication noise, reflected in a reduced representation of high-frequency energy (Fagniart et al., 2024b; 2024c), directly mirroring the limitations of high-frequency encoding by CI.

- Voiced and voiceless plosive consonants: their distinction is based on temporal correlates (Voice Onset Time) known to be well encoded by the CI. However, the evidence in the literature is contradictory (Bouton et al., 2012; Giezen et al., 2010; Grandon et al., 2017; Horga & Liker, 2006; Peng et al., 2019; Uchanski & Geers, 2003), indicating variability in the ability of children with CI to perceive and produce these voicing cues.

The production capacities associated with these different segments, assessed by acoustic measurements, have been correlated with linguistic performance in the phonological, lexical, and morphosyntactic domains.

The objectives were as follows:

- to compare the performance of children with CI to that of their hearing peers;

- to examine the relationships between acoustic and linguistic (lexical and morphosyntactic) variables using factorial analysis;

- to determine whether this analysis can be used to identify differentiated performance profiles, highlighting perceptual-productive profiles that compensate for acoustic limitations and are associated with good linguistic performance.

- to observe the developmental profiles of a subgroup of children through a re-test conducted one year later, to examine the developmental trajectory of all the skills investigated.

Based on previous research (Fagniart et al., 2024a; Fagniart et al., 2025a; Fagniart et al., 2025b), we expect children with CI to show lower acoustic differentiation on the vulnerable phonological contrasts than TH children. We also hypothesised that reduced acoustic differentiation would be associated with lower linguistic performance.

METHODS

Participants

A group of typically hearing children (TH group) and a group of children with cochlear implants (CI group) were recruited for the study. The CI group consisted of 23 French-speaking children (mean age: 67 ± 15 months) with profound congenital bilateral deafness. Of these, 22 had bilateral implants and one child had a unilateral implant. All participants in the CI group received oralist auditory rehabilitation, both at rehabilitation centers and within their families. Nineteen children with CI were monolingual French speakers. Four children with CI were bilingual, speaking French and a family language different from French: Arabic (n = 2), Portuguese (n = 2).

The CI group was subdivided according to exposure to French Cued Speech (CS) : 8 children with no exposure (CS0), 8 children exposed to CS during speech therapy sessions (2–3 sessions per week – CS− group), and 7 children exposed both in therapy and in the family environment (CS+ group). The group was also categorized according to age at implantation: children who received their first implant before 16 months were classified as early implanted, whereas those implanted after 16 months were classified as late implanted (n = 11). The 16-month threshold was selected in line with studies showing substantial benefits of implantation before 18 months (Sharma et al., 2020); given the distribution of implantation ages in the sample, it was lowered to 16 months to obtain subgroups of comparable size. The characteristics of the children in the CI group are presented in table 1.

The TH group included 47 monolingual French-speaking children with a mean age of 56 ± 13 months, with no learning delays or hearing impairments. The children in this group were selected so that they could be matched with the children in the CI group either for chronological age or for hearing age. All participants took part in an initial testing session (T1). The entire CI group was contacted again for a second test one year later; thirteen children were able to participate in this assessment (T2), allowing for a longitudinal comparison.

Tasks

Four tasks were administered to all children. These tasks were selected to obtain controlled productions suitable for acoustic analyses (picture naming) as well as narrative productions, one elicited and one free, to obtain semi-spontaneous speech samples suitable for lexical and morphosyntactic analyses. A morphemic processing task was also administered to examine morphosyntax on its receptive side, in connection with certain perceptual difficulties reported in CI users (notably the processing of the vowel nasality feature). The performance of the groups of children across all these tasks has been described in detail in previous studies to which the reader is referred (Fagniart et al., 2024b; Fagniart et al., 2025b). The present study aims to examine these different measures jointly within a multivariate framework.

Word picture naming task

A picture-naming task was first proposed to study children's productions from an acoustic and phonological perspective. Forty-eight target words were selected to cover all French phonemes in initial, medial, and final syllable positions. The items were chosen for their early age of acquisition (according to Chalard et al., 2003) to facilitate recall (see Philippart De Foy et al., 2018, for more details).

The target images were presented one by one in a booklet; the child had to name each image orally. In the case of no response or a response that did not match the target (e.g., semantic paraphasia, random response), prompts were provided: first semantic clues (e.g., " we use it when it is raining" for "parapluie" */paʁaplɥi/* umbrella), then, if necessary, a phonological cue by presenting the initial phoneme (e.g., "it starts with /s/" for "souris" */suri/* mouse). If the child still did not produce the target word, the experimenter pronounced it and asked for a repetition.

Sentence/word-picture matching task

In a morpheme processing task consisting of sentence/word-picture matching, a word or short sentence was presented auditorily (audio recordings), and the child had to choose between two pictures, the target and a distractor, the latter forming a minimal pair with the target. The task comprised a total of 28 items: 13 number markers (e.g., "il va" */il va/* he goes vs. "ils vont" */il vɔ̃/* they go), 7 gender markers (e.g., "boulanger" */bulɑ̃ʒe/* male baker vs. "boulangère" */bulɑ̃ʒɛʁ/* female baker) and 8 minimal pairs (e.g., "bain" */bɛ̃/* bath vs.

Table 1

Descriptive table of participants in the CI group

Subject	Sex	Chronological age (years; months)	Age at first implantation (months)	Implantation age group	Implantation type	Linguistic environment	CS exposure group	T2 retest
CI1	M	4;6	9	< 16M.	Bilateral	Monolingual	CS0	/
CI2	M	6;5	39	> 16M.	Bilateral	Monolingual	CS0	/
CI3	F	5;10	15	< 16M.	Bilateral	Monolingual	CS0	/
CI4	F	6;7	7	< 16M.	Bilateral	Monolingual	CS0	/
CI5	F	6;6	31	> 16M.	Bilateral	Monolingual	CS+	/
CI6	F	4;7	7	< 16M.	Unilateral	Monolingual	CS+	/
CI7	F	7;3	13	< 16M.	Bilateral	Monolingual	CS-	/
CI8	M	4;7	13	< 16M.	Bilateral	Monolingual	CS-	/
CI9	M	4;9	13	< 16M.	Bilateral	Monolingual	CS+	Yes
CI10	M	4;6	12	< 16M.	Bilateral	Monolingual	CS-	Yes
CI11	F	4;6	18	> 16M.	Bilateral	Monolingual	CS-	Yes
CI12	M	5;6	9	< 16M.	Bilateral	Bilingual French-Portuguese	CS-	Yes
CI13	F	7;3	24	> 16M.	Bilateral	Bilingual French-Portuguese	CS-	Yes
CI14	G	7;10	26	> 16M.	Bilateral	Bilingual French-Arabic	CS-	Yes
C15	G	6;11	23	> 16M.	Bilateral	Bilingual French-Arabic	CS-	Yes
C16	F	6;9	20	> 16M.	Bilateral	Monolingual	CS+	Yes
C17	M	6;0	20	> 16M.	Bilateral	Monolingual	CS0	/
CI18	F	3;9	23	> 16M.	Bilateral	Monolingual	CS0	Yes
CI19	F	5;0	12	< 16M.	Bilateral	Monolingual	CS+	/
CI20	F	3;8	32	> 16M.	Bilateral	Monolingual	CS-	Yes
CI21	M	4;11	11	< 16M.	Bilateral	Monolingual	CS0	Yes
CI22	F	6;7	17	> 16M.	Bilateral	Monolingual	CS+	Yes
CI23	F	5;0	13	< 16M.	Bilateral	Monolingual	CS+	Yes

"banc" /bɑ̃/ bench). These grammatical and lexical distinctions were based on various phonological contrasts: oral/nasal (n = 10), oral/oral (n = 3) or nasal/nasal (n = 3) vowel substitutions, as well as phonemic additions (n = 12).

Two images (target, distractor) were presented on a tablet. The stimuli were played through speakers (Bose Soundlink) at a controlled average level of 60 dB controlled with a Decibel Meter. Five training items preceded the task to ensure understanding of the instructions and adjust the volume.

Narrative production tasks

Two storytelling tasks were proposed to analyze morphosyntactic production skills: a guided and a free narration. The guided storytelling task began with the presentation of an animated story on a tablet, with the animation providing visual support while a recorded narrator told the story. To prevent the child from focusing exclusively on one channel or the other, narration and animation alternated without overlapping. At the end of the presentation, the child was asked to retell the story based on the animated images. The story presented was designed to introduce plot twists requiring various tenses and verb forms (past, future, conditional) as well as gender and number markers, to encourage the production of a variety of grammatical markers. Free narration consisted of presenting the widely used clinical and research picture book "Frog, Where Are You?" (Mayer, 1969) without text, during which the child had to tell the story.

Procedure

The four tasks were performed in a quiet environment, in the presence of the experimenter and, in some cases, the speech therapist of each child. The order was as follows: naming, guided narration, sentence/word-picture matching task, then free narration. The entire test lasted 35 to 60 minutes, with breaks between tasks. All productions were recorded using a Zoom H5 portable audio recorder; responses to the morpheme processing task were recorded during the session. The tests were repeated one year later (subgroup of 13 children) in exactly the same manner.

Measures

Various measures were collected to describe production profiles according to acoustic and linguistic dimensions (phonology, morphology, lexicon, morphosyntax). The measures, detailed below, were averaged per child to feed factor analyses representing each child on the extracted dimensions.

Acoustic measurements

Acoustic measurements were conducted only on the productions collected during the picture-naming task. A complete description of the measurements and the semi-automatic signal analysis procedure is provided in previous studies (Fagniart et al., 2025a; Fagniart et al., 2024b); only the essential elements are included here.

- Vowels: the objective was to document (i) the specific oropharyngeal configuration of the target vowel via formant measurements, as these indices are more easily exploitable when the formants are distinct and associated with visible articulatory dimensions (opening, rounding), and (ii) the degree of nasal resonance, as the oro-nasal/oral distinction is based on subtle acoustic indices (i.e., the amplitude ratio of the first harmonics) that are particularly vulnerable to processing by the CI. The formants were examined for the oropharyngeal configuration; nasal resonance was indexed by Nasalization from Acoustic Features (NAF, Carignan et al., 2023). A total of 6605 vowels were analyzed. To study the phonetic implementation strategies of the nasal/oral phonological contrast, pairwise comparisons were made, based on phonetic proximity (/ɑ̃/-/ɔ/, /ɑ̃/-/o/, /ɔ̃/ -/o/, /ɔ̃/-/ɔ/, /ɔ̃/-/u/, /ɛ̃/-/a/) and phonological proximity (/ɑ̃/-/a/, /ɔ̃/-/ɔ/, /ɛ̃/-/ɛ/) of French vowels (Borel, 2015). For each child, each nasal vowel produced was paired with all phonetically or phonologically similar oral vowels, generating 30,402 pairs and allowing acoustic indices to be compared within each pair. Euclidean distances in the F1-F2-F3 (Bark) plane and NAF differences were calculated for each pair. Two measures were selected for factor analysis:

o F1-F2-F3 Euclidean distances between phonological and phonetic nasal/oral pairs;

o NAF differences between phonological and phonetic nasal/oral pairs.

- Fricatives: acoustic characterization was based on recent measurements (Shadle et al., 2023) to identify spectral peaks related to the place of articulation (location of obstruction) and the quality of friction noise via intensity ratios in the low, mid, and high frequency bands. 1,917 fricatives were analyzed. Three measurements were selected:

o differences in spectral peaks between front fricatives (/f/-/v/) and mid fricatives (/s/-/z/), and between mid (/s/-/z/) and back fricatives (/ʃ/-/ʒ/) (SP_1_2, SP_2_3);

o AmpDiff: ratio of mid-range vs. low-frequency energy in fricative noise;

o LevelD: ratio of high vs. mid-frequency energy. Good fricative noise has a significant amount of energy in the mid and especially high frequencies: we therefore expect high AmpDiff values (mid > low) and low LevelD values (high proportion of energy in high frequencies).

- Plosives (voicing): the Voice Onset Time (VOT) was measured on 3,012 occlusives. A composite measurement was calculated: the difference between the average VOT of voiced sounds and that of unvoiced sounds.

Linguistic measures

The complete results obtained by the two groups of children in the various language tasks are described in previous studies (Fagniart et al., 2024b; Fagniart et al., 2025b). The following sections aim to clarify the measures used for factorial analyses.

Phonological score

The productions from the naming task were annotated by an examiner and then verified by the first author in Phon 3.1 (Hedlung & Rose, 2020). The software compares the target form and the annotated production and extracts various indices of phonological accuracy. Here, we use an overall score: the percentage of correct phonemes (PCP).

Sentence/word-picture matching task scores

Scores were calculated for all marker categories (gender, number) as well as for minimal pairs, taking into account underlying phonological mechanisms (oral/nasal, oral/oral, nasal/nasal contrasts, phonemic addition). The scores were obtained by subtracting the normalized, centered, and standardized values of the hit rate (correct detections) and false alarm rate (incorrect detections), according to signal detection theory (MacMillan & Creelman, 1991). The extreme values 0 and 1 were adjusted to 0.01 and 0.99 to allow transformation into Z-scores. For factorial analyses, the total score (SWPMT_tot) and the score restricted to items contrasting oral/nasal morphophonological alternations (SWPMT_or_nas) were used.

Narrative production scores and error types

The narrative productions (audio recordings) were transcribed in PHON (Hedlund & Rose, 2020), then exported to CLAN (MacWhinney, 2000) for morphosyntactic annotation using MOR and POST (Parisse & Le Normand, 2000). The KidEval program was used to extract various indices of morphosyntactic development and to categorize function words and verb tenses.

The following indices were selected for factor analysis:

- Mean length of utterances in morphemes (MLUm), an index frequently used to reflect morphosyntactic development

- Number of reflexive pronouns (Refl_pro)

- Frequency of use of the imperfect tense among verbs (Simple_past)

These indices were chosen based on findings from a previous study (Fagniart et al., 2025b), which showed significantly greater vulnerability of these indices among children with CI compared to their hearing peers of the same age.

Morphosyntactic production errors were identified and categorized by the first author (Fagniart et al., 2025b). Only omissions of determiners before monosyllabic nouns (om_det_1syll) vs. bisyllabic nouns (om_det_2syll) were retained for factor analysis, as they were more frequent in the CI group and modulated by age of implantation and CS exposure. Finally, a lexical diversity index, the D index, was calculated using the CLAN VOCD procedure (Duran et al., 2004), providing a probability of introducing a new word regardless of the size of the corpus.

Statistical analysis

As the aim of the present study was to characterize the children's language performance based on all the measures collected, the analyses were conducted from a multivariate perspective using factor analyses. This type of analysis makes it possible, by examining the correlations between variables, to reduce the set of variables into dimensions, or components, that summarize the dataset. This procedure allows all children to be positioned according to their performance across a reduced number of dimensions, thereby making it possible to observe trends in performance profiles while taking into account all the variables considered. A principal components analysis (PCA) was performed using FactoMineR (Husson et al., 2024) and graphical representations were produced using factoextra (Kassambara & Mundt, 2020). The analyses focused on a dataset averaged by child, comprising aggregated (mean) acoustic measurements converted into z-scores, including:

- Acoustic variables related to the distinction between nasal and oral vowels: averages of differences (phonological and phonetic pairs) for nasal resonance (NAF) (NAF_phono, NAF_phone) and for Euclidean distances F1-F2-F3 (F123_phono, F123_phone).

- Acoustic variables related to the production of fricatives: differences in mean spectral peaks between */f-v/* and */s-z/* (SP_1_2), and between */s-z/* and */ʃ-ʒ/* (SP_2_3) and mean values of AmpDiff and LevelD ratios.

- Acoustic variable related to the production of voiced and unvoiced stops: difference in voice onset time values between voiceless and voiced stops (VOT_UV_V).

- Variables related to the morpheme processing task: total score (TM_tot) and oral/nasal score (TM_or_nas).

- Variables related to the naming task: PCP in naming and percentage of recall on the first attempt (Naming).

Table 2

Description of the linguistic and acoustic variables used in the principal component analysis

Variable	Description	Linguistic skill assessed	Task
PPC	Percentage of correct phonemes	Phonology (production)	Task 1: picture naming
Naming	Number of correct spontaneous naming responses	Lexicon	
NAF_phone	Acoustic cues of nasality measuring the presence of nasal resonance in vowels (phonetic and phonological pairs)	Phonetics – oral/nasal vowels	
NAF_phono		Phonetics – oral/nasal vowels	
F1_F2_F3_ phone	Euclidean distance calculated from the formants F1–F2–F3 between oral and nasal vowels (phonetic and phonological pairs)	Phonetics – oral/nasal vowels	
F1_F2_F3_ phono		Phonetics – oral/nasal vowels	
AmpDiff	Energy ratio between mid- and low-frequency ranges in fricative noise	Phonetics – fricative consonants	
LevelD	Energy ratio between high- and mid-frequency ranges in fricative noise	Phonetics – fricative consonants	
SP_1_2	Difference in spectral peaks distinguishing places of articulation: – between anterior and medial fricatives (_1_2) – between medial and posterior fricatives (_2_3)	Phonetics – fricative consonants	
SP2_3		Phonetics – fricative consonants	
VOT_UV_V	Difference in Voice Onset Time (VOT) between voiceless and voiced plosive consonants	Phonetics – plosive consonants	
TM_tot	Total score on the morpheme processing task	Morphophonological processing	Task 2: morpheme processing
TM_or_nas	Score for items involving the oral–nasal contrast		
D	Lexical diversity index	Lexicon	Tasks 3–4: narratives
MLUm	Mean Length of Utterances in morphemes	Morphosyntax	
Simple_past	Frequency of use of the imperfect tense		
Refl_pro	Number of reflexive pronouns used		
Det_del_1syll	Determiner omissions before monosyllabic words		
Det_del_2syll	Determiner omissions before bisyllabic words		

- Variables related to narration tasks: MLUm, D index, frequency of use of the imperfect tense (Simple_past), number of reflexive pronouns (Refl_pro), omissions of determiners before monosyllabic words (Det_del_1syll) and bisyllabic words (Det_del_2syll).

All the variables collected in each task, together with their objective and the associated linguistic component assessed, are summarized in table 2.

The characteristics of the children were introduced as additional variables (without contributing to the construction of the axes) to examine their distribution along the dimensions. After extracting the dimensions, ascending hierarchical classifications (Husson et al., 2024) were carried out to form performance clusters summarizing the selected axes. The method is based on dissimilarity indices between individuals and an aggregation index between clusters, resulting in a dendrogram. This approach was chosen to typologize profiles independently of hearing status. The classification was based on the first three dimensions of the factor analysis, representing 52.9% of the explained variance. The dendrogram was used to set an optimal cut-off point to obtain a sufficiently discriminating partition without oversimplifying, according to the procedure described by Cornillon et al. (2018).

To identify cluster profiles, comparative analyses were performed using generalized linear mixed models, controlling for the random subject effect, with lme4 (v. 1.1-34; Bates et al., 2015) and emmeans (Lenth et al., 2023) under R (R Core Team, 2022).

RESULTS

Results at T1

Principal components analysis (PCA)

Factor analysis extracted 19 dimensions, corresponding to the number of variables included in the model (see table 2). Only the first three dimensions, which account for 52.9% of the explained variance, are described here. Figure 1 illustrates the contribution of the different variables to the three dimensions.

Dimension 1 (30.7% of variance explained) appears to be directly related to linguistic performance. The following variables contribute most to the positive values on this axis: Mean Length of Utterances in morphemes (MLUm: 0.8), Percentage of Correct Phonemes (PCP: 0.8), number of spontaneous evocations in naming (0.8), and score on the sentence/word-picture matching task specific to nasal and oral vowels (0.73). Strong correlations with Dimension 1 are also observed for the lexical diversity index D (0.61) and the use of the imperfect tense in narratives (0.62). On the negative side of the axis, the omission of articles before monosyllabic (-0.64) and disyllabic (-0.75) words are the major contributors. This means that positive values on Dimension 1 are associated with higher linguistic skills, whereas negative values are associated with lower skills and a greater number of morphosyntactic errors.

Dimension 2 (11.3% of explained variance) is directly associated with the acoustic marking of

Figure 1

Circle of correlations between initial variables for dimensions 1 and 2 (left) and 2 and 3 (right), according to their degree of contribution to the construction of the axes (indicated by the length of the arrows)

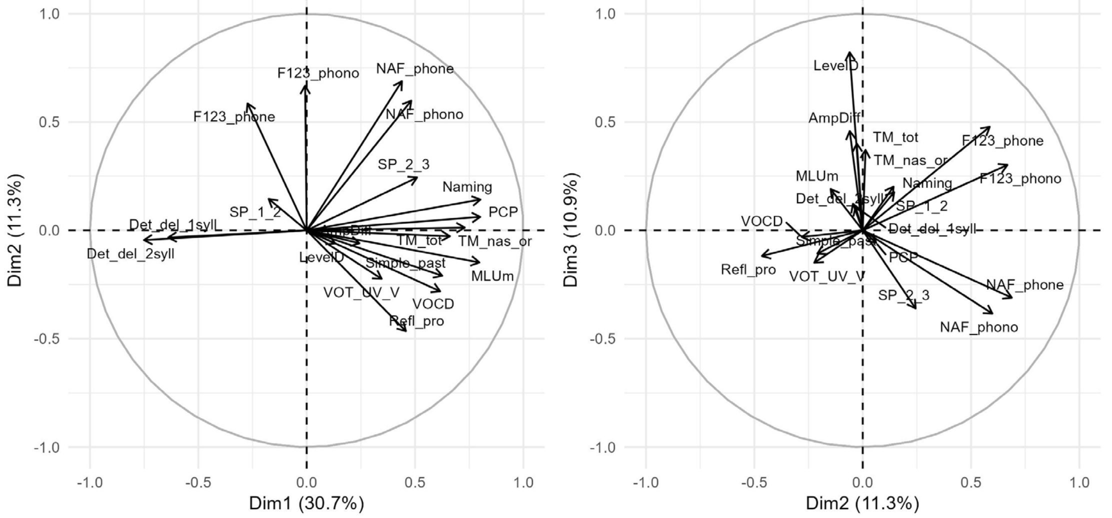
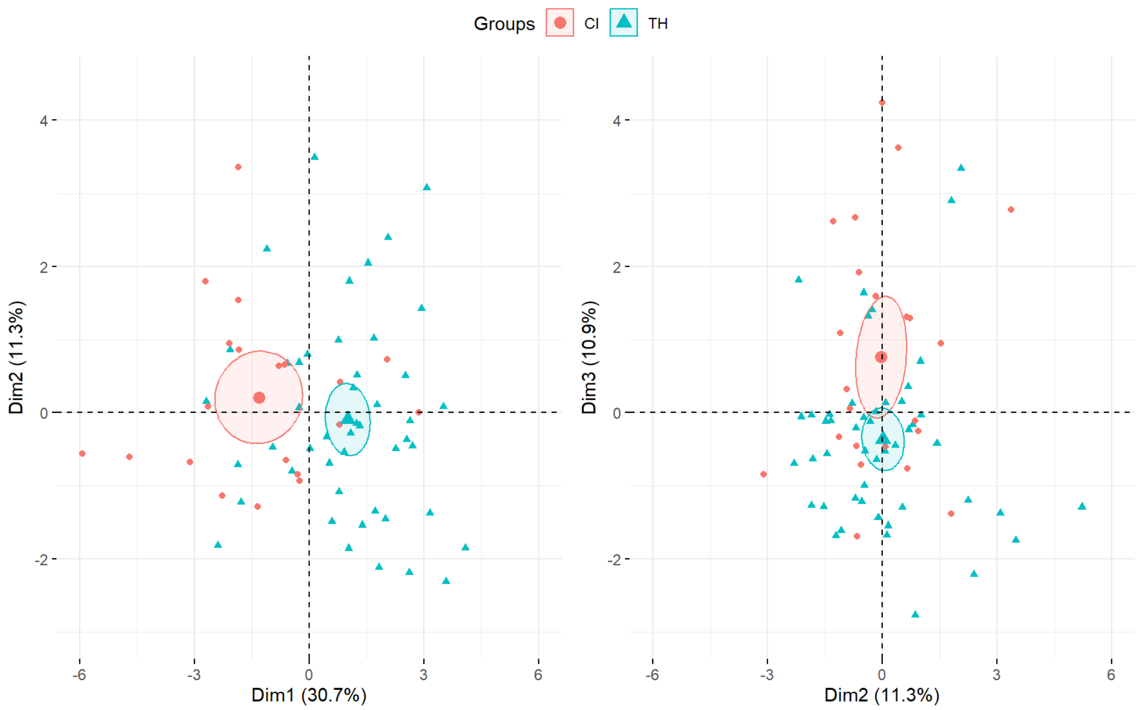


Figure 2

Representation of participants according to dimensions 1 and 2 (left) and 2 and 3 (right), for the CI and TH groups, with 95% confidence interval ellipses



the oral–nasal distinction. Positive values on this axis are mainly driven by variables reflecting nasal resonance cues (NAF_phono: 0.59; NAF_phone: 0.69) as well as by the Euclidean distances between vowels based on the F1–F2–F3 formant structure (F123_phono: 0.67; F123_phone: 0.59). This dimension reflects a clearer acoustic distinction between oral and nasal vowels, independently of the specific acoustic strategy used to encode it, whether through nasal resonance cues or formant-based differences.

Dimension 3 (10.9% of explained variance) appears to reflect differences in the acoustic cues used to encode phonetic contrasts. Positive values are mainly associated with higher LevelD values (0.82), indicating fricative productions in which energy is relatively more concentrated in the mid-frequency range than in the high frequencies, as well as greater formant-based distinction between oral and nasal vowels (F123_phono: 0.3; F123_phone: 0.47). In contrast, negative values are associated with stronger marking of nasality through nasal resonance (NAF_phono: -0.38; NAF_phone: -0.31) and with clearer distinctions between medial and posterior places of articulation for fricatives (SP2_3: -0.36). Overall, this axis appears to oppose productions relying more on spectral energy distribution and formant structure to those relying more on nasality cues and place-of-articulation contrasts.

Figure 2 shows a clear tendency for the CI group to be on the negative side of Dimension 1 compared to the TH group (positive side), indicating lower values on language scores. Dimension 2 does not discriminate between the groups, which are located close to zero. The distribution on Dimension 2 and 3 highlights a trend on Dimension 3: the CI group is positioned more on the positive side compared to the TH group. This reflects a stronger marking of the oral/nasal opposition via the F1-F2-F3 distances and higher values of levelD and ampDiff. However, there is significant intra-group variability among CI children.

Hierarchical Ascendant Classification (HAC)

To categorize performance profiles (acoustic and linguistic) in detail, unsupervised analyses using hierarchical classification were conducted based on the three dimensions of PCA. The analysis identified four performance Clusters (see figure 3).

Cluster 1 stands out clearly on Dimension 1 and

Figure 3

Distribution of the four clusters of participants along dimensions 1 and 2 of the PCA (left) and dimensions 2 and 3 (right)

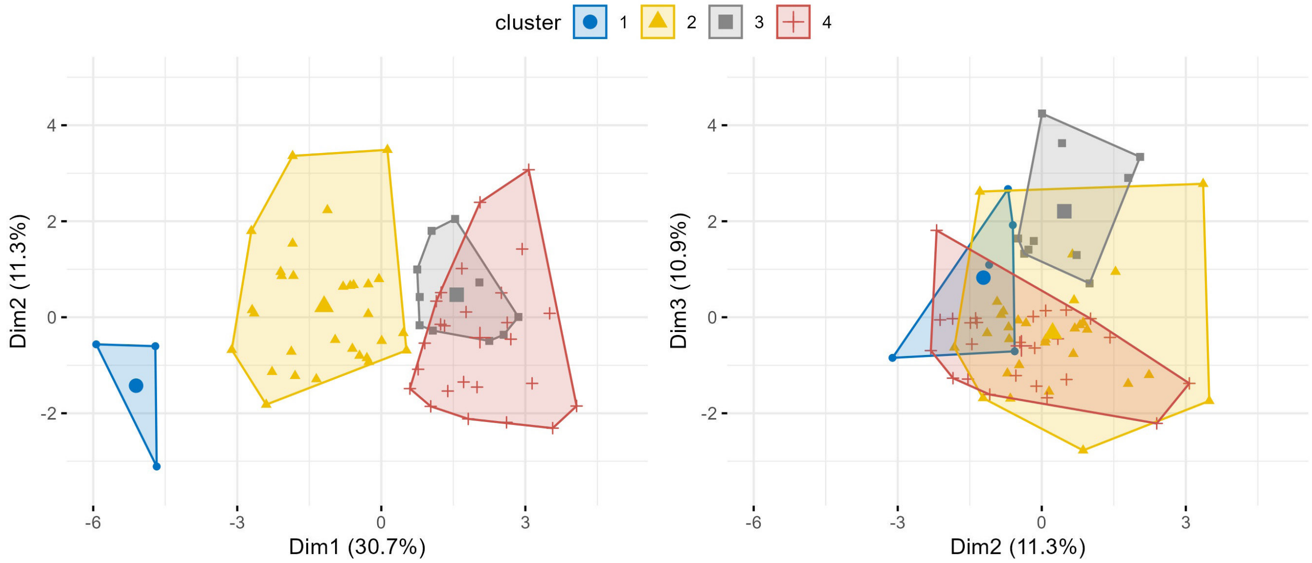


Table 3

Numbers or averages of the different clusters according to hearing status, chronological and hearing age, with associated intergroup comparison tests (χ^2 or Kruskal-Wallis)

Variable	Groups	Cluster 1	Cluster 2	Cluster 3	Cluster 4	p-values
Auditory status (N)	CI	5	14	4	0	<.001
	TH	0	17	6	25	
	Total	5	31	10	25	
Chronological age (months)	CI	71.6	64.3	72.7	NA	NS
	TH	NA	47.7	54.1	63.5	<.001
	Total	71.6	55.1	61.6	63.5	<.001
Auditory age (months)	CI	49.8	47.4	54.5	NA	NS
	TH	NA	47.7	54.1	63.5	<.001
	Total	49.8	47.4	54.3	63.5	<.001

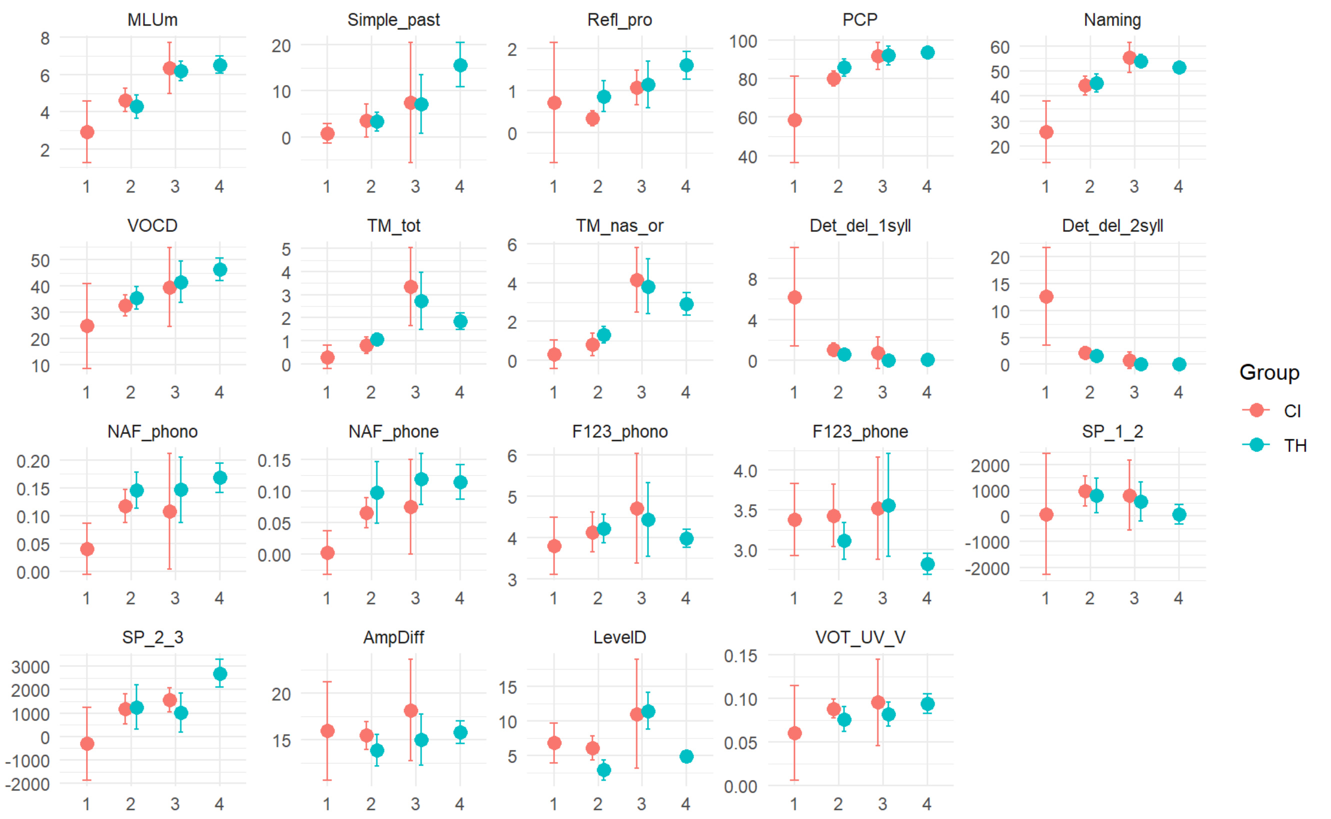
corresponds to the lowest linguistic performance; Cluster 2 is placed in an intermediate position; Clusters 3 and 4 are clearly on the right side of the Dimension 1 axis. Cluster 1 also differs in its negative values on Dimension 2, with the other clusters being close to zero. On Dimension 3, the trends are diverging: Clusters 1 and 3 are positive (especially for Cluster 3), Cluster 4 is negative, and Cluster 2 shows significant variability.

Various variables were analyzed to characterize the clusters. Table 3 shows the numbers of subjects according to hearing status and the mean ages of each cluster, as well as the p-values of the χ^2 (independence) or Kruskal-Wallis tests.

We observe that Cluster 1 includes only CI children (n = 5), while Cluster 4 includes only TH children (n = 25). Clusters 2 and 3 have equivalent proportions of CI and TH children. In terms of chronological age, TH children are younger in Clusters 2 than in Clusters 3 and 4, while children in Cluster 1 are the oldest among the CI children. In terms of hearing age, the CI children are statistically equivalent across the three Clusters. It should be noted that in Cluster 2, the auditory ages of CI and TH children are equivalent. The chi-square tests indicated no significant association between clusters and CS exposure groups ($\chi^2(4) = 5.24$, $p = .30$) or age at implantation groups ($\chi^2(2) = 1.44$,

Figure 4

Mean values with 95% confidence intervals for the initial PCA variables, grouped by clusters (x-axis) and differentiated according to hearing status (color)



p = .50), suggesting that these variables are similarly distributed across clusters.

To further explore the general findings from the PCA, comparisons of the raw values of the different variables were made and are summarized in figure 4, allowing for a detailed characterization of the four Clusters.

- Cluster 1 (CI children only): Children in Cluster 1 show the lowest linguistic performance overall, with lower Mean Lengths of Utterances in morphemes (MLUm), Percentage of Correct Phonemes (PCP), and spontaneous naming scores than the other clusters. For lexical diversity (D) and the morpheme processing task (total and oral–nasal items), their performance is similar to Cluster 2 but remains lower than that of Clusters 3 and 4. From an acoustic perspective, oral–nasal marking through the NAF index is weaker than in the other clusters, although formant-based distances (F1–F2–F3) are comparable. For fricatives, the distinction between medial and posterior places of articulation is less clearly marked than in the other clusters. For plosives, the contrast between voiced and voiceless VOT is also less pronounced than in Cluster 4.

- Cluster 2 (equivalent CI / TH proportions): Cluster 2 shows intermediate linguistic performance. Scores for MLUm, PCP, and spontaneous naming are higher than in Cluster 1 but remain lower than in Clusters 3 and 4, and lexical diversity (D) is lower than in Cluster 4. Acoustically, oral–nasal marking through NAF is stronger than in Cluster 1. In addition, formant-based distances for oral–nasal contrasts (phonetic pairs) are greater than in Cluster 4. The distinction between medial and posterior fricatives is clearer than in Cluster 1 but less marked than in Cluster 4, while LevelD values are comparable to those of Clusters 1 and 4. No differences between clusters are observed for the voiced–voiceless VOT contrast.

- Cluster 3 displays high linguistic performance, with MLUm, PCP, lexical diversity (D), and spontaneous naming scores higher than those of Clusters 1 and 2 and comparable to those of Cluster 4. For oral–nasal marking based on the NAF index, values are similar to those observed in Clusters 2 and 4. However, formant-based distances (for phonological pairs) are higher than in Cluster 4. For fricatives, the distinction between medial and posterior places of articulation is weaker than in Cluster 4, and this cluster shows the highest LevelD values.

- Cluster 4 (TH children only): Cluster 4 shows the strongest overall linguistic performance, often comparable to Cluster 3 but characterized by more frequent use of the simple past tense and reflexive pronouns. Phonetically, formant-based distances for oral–nasal contrasts are lower than in some other clusters. In contrast, this cluster shows the clearest distinction between medial and posterior fricatives, indicating a particularly robust marking of place of articulation.

The average differences between Clusters for F1-F2-F3 distances (phonological pairs), spectral peaks (front fricatives vs. mid fricatives), and the ampDiff index are statistically equivalent. For Clusters 2 and 3 (equivalent CI/TH proportions), tests examined the effect of hearing status, cluster, and their interaction. Higher values in TH, regardless of cluster, are observed for PCP ($\chi^2(1) = 3.5$; $p = .05$) and for the oral/nasal item score ($\chi^2(1) = 3.4$; $p = .06$). Acoustically, a group effect in favor of THs appears for NAF (phonological pairs: $\chi^2(1) = 4.39$; $p = .03$; phonetic: $\chi^2(1) = 3.42$; $p = .05$). Higher values for the ampDiff ($\chi^2(1) = 4.44$; $p = .03$) and levelD ($\chi^2(1) = 3.41$; $p = .05$) ratios were noted in the CIs.

Results at T2

A subgroup of 13 children with CI from the total sample repeated all the tasks one year after T1 (T2).

T1–T2 comparisons

Repeated measures analyses show significant progress for various measures related to language skills:

- MLUm ($\beta = 1.26$; SE = 0.25; $t(12) = 5.04$; $p < .001$)

- Reflexive pronouns ($\beta = 4.5$; SE = 1.15; $t(12) = 3.95$; $p = .001$

- PCP ($\beta = 5$; SE = 1.4; $t(12) = 2.55$; $p = .003$)

- Number of spontaneous evocations in the naming task ($\beta = 7$; SE = 2.02; $t(12) = 3.46$; $p = .004$)

- Lexical diversity index D ($\beta = 11.4$; SE = 7.07; $t(12) = 2.81$; $p = .01$).

Acoustically, changes were observed for fricatives: improved median/posterior distinction ($\beta = 1203$; SE = 276; $t(12) = 4.36$; $p < .001$) and increase in ampDiff ($\beta = 1.57$; SE = 0.75; $t(12) = 2.1$; $p = .05$). For most measurements, variability decreases at T2.

Principal components analysis and hierarchical ascendant classification

The subgroup data were projected onto the initial factorial plane (predicted coordinates on the dimensions obtained at T1), allowing for a comparison of the T1 vs. T2 positions (figure 5).

On Dimension 1, according to the participants, there is a shift towards positive values, indicating linguistic improvement. On Dimension 2, the shifts are mixed (towards positive: N = 7; towards negative: N = 6). On Dimension 3, there is a more general trend towards negative (N = 10), which may indicate better use of nasal resonance cues for oral/nasal opposition and/or more adequate phonetic realization of fricatives (better distinction of places; better friction noise). Some participants (e.g., CI10, CI12) show very small shifts between T1 and T2.

Based on the projected T2 coordinates, it was possible to locate T2 performances in relation to the clusters defined at T1. Table 4 shows the assignment to clusters at T1 and T2, as well as chronological age (CA) and hearing age (HA).

Four children (30.7%) changed clusters: CI14 moved from cluster 1 to cluster 2, CI18 and CI23 moved from cluster 2 to cluster 3, and CI16 moved from cluster 3 to cluster 4. Nine children (69.3%) remained in the same cluster as at T1.

For CI16 (who joins Cluster 4 at T2), the changes mainly concern: an increase in PCP and spontaneous evocations, a decrease in determiner omissions before monosyllabic words (with an increase before disyllabic words), an increase in oral/nasal marking via the oropharyngeal configuration, and better distinction of the places of articulation of fricatives. In the other subjects, the improvements are more related to overall linguistic scores: an increase in MLUm, the use of the imperfect tense and personal pronouns in narratives, and lexical diversity. CI18 also shows better marking of the oropharyngeal configuration for oral/nasal vowels, better distinction of the places of articulation of fricatives, and higher ampDiff values.

Figure 5

Representation of children at times T1 and T2 on dimensions 1 and 2 (left) and on dimensions 2 and 3 (right). The arrows connect the coordinates between the two assessments

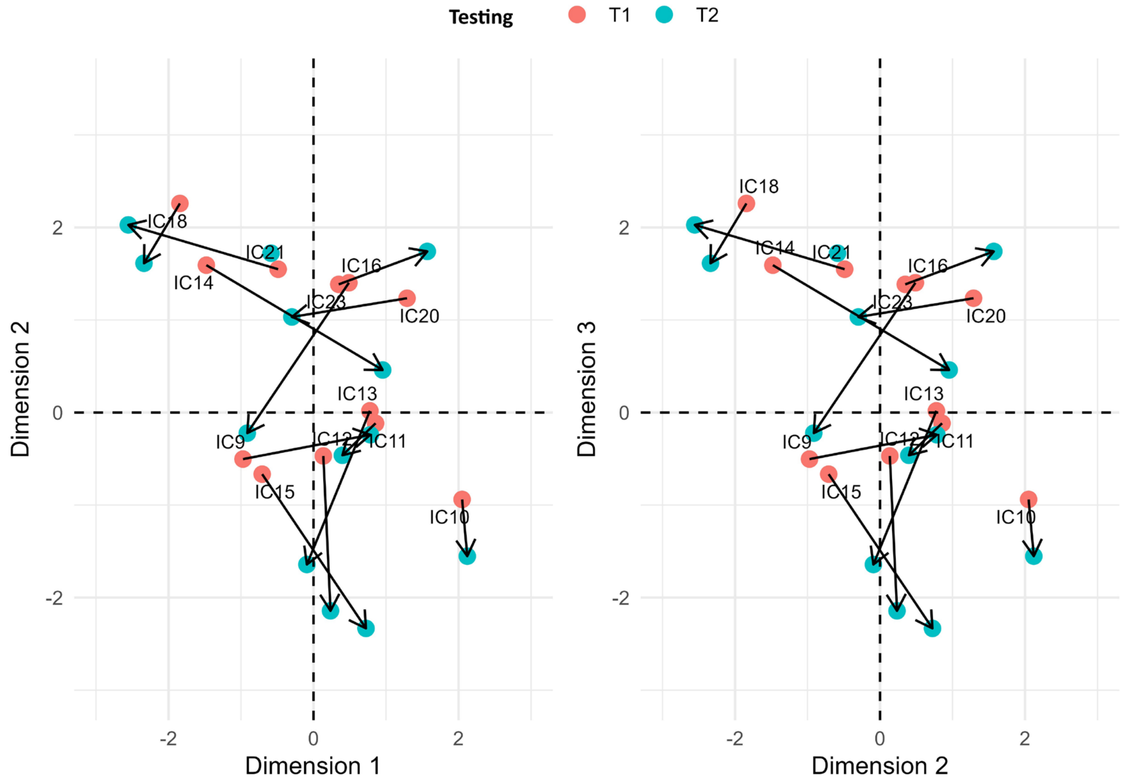


Table 4

Chronological age (CA) and hearing age (HA), as well as cluster membership during tests 1 and 2, for the subgroup of children with cochlear implants (CI).

Subjects	**CA - T1**	**HA - T1**	**Cluster - T1**	**CA - T2**	**HA - T2**	**Cluster - T2**
CI9	57	44	2	69	56	2
CI10	54	42	2	66	54	2
CI11	54	36	2	66	48	2
CI12	66	42	2	71	57	2
CI13	87	61	2	99	73	2
CI14	94	71	1	106	83	**2**
CI15	83	63	2	95	75	2
CI16	81	61	3	96	76	**4**
CI18	45	33	2	60	48	**3**
CI20	44	33	2	58	47	2
CI21	59	42	3	74	57	3
CI22	79	66	3	61	48	3
CI23	60	39	2	75	54	**3**

Note. *Changes in cluster membership between T1 and T2 are highlighted in bold in the last column.*

DISCUSSION

The objective of this study was to examine the production profiles of children with cochlear implants (CI) and children with typical hearing (TH) for three types of speech sounds whose acoustic correlates pose different challenges for the CI (nasal/oral vowels, fricative and occlusive consonants), in relation to their phonological, lexical, and morphosyntactic language skills. To do this, factor analyses were conducted, and then clusters were formed using hierarchical classification. Various influencing factors were considered: chronological/auditory age, exposure to Cued Speech, and age at first implantation. A subgroup of CI children also repeated the tasks one year after the first session, allowing for a longitudinal comparison of performance.

Factor analysis revealed three dimensions explaining approximately 50% of the total variance. The first dimension was directly related to overall linguistic performance: phonological scores, number of spontaneous evocations in naming, lexical diversity index, scores on the sentence/word-picture matching task, and indices of morphosyntactic development. This dimension clearly discriminated between children according to their hearing status, with CI children generally showing lower linguistic performance. The combination of different skills, phonological, lexical, and morphosyntactic, suggests relatively homogeneous joint development in our sample. This may seem to contrast with some studies that attribute a special status to the lexicon, which may be better preserved due to the greater perceptual and conceptual salience of lexical units (Caselli et al., 2012; Duchesne et al., 2009; Le Normand & Moreno-Torres, 2014; Rinaldi et al., 2013). However, this finding is not universally confirmed, with other studies (Cambra et al., 2021; Le Normand & Moreno-Torres, 2014) also highlighting an increased vulnerability of CI children in terms of lexical skills, especially in narrative tasks. These discrepancies may be explained by methodological differences: studies concluding that lexical abilities are preserved most often rely on formal tests (picture naming or pointing tasks), whereas narrative production involves more complex linguistic processes that are closer to natural communication situations. Our results therefore suggest that lexical development may also represent a point of vulnerability in some children with cochlear implants, particularly in more ecological language production tasks.

Dimensions 2 and 3 of the PCA were linked to acoustic production profiles: high values on axis 2 indicated the ability to distinguish between oral and nasal sounds regardless of the production strategy (oronasal resonance vs. specific oropharyngeal configuration); dimension 3 specifically differentiated between these two strategies. On this dimension, the groups of children were again clearly separated: CI children tended to mark the oral/nasal opposition with the oropharyngeal configuration, unlike TH children, who used oral resonance more often than nasal resonance. This result was expected, as it corroborates observations from repetitions of pseudo-words containing nasal and oral vowels (Fagniart et al., 2025a). This performance profile appears to be directly related to the perceptual limitations associated with cochlear implants, which in turn influence production strategies. While the acoustic correlates underlying the nasal–oral contrast related to resonance are highly complex and therefore more likely to be poorly encoded by the implant, the formant patterns associated with oropharyngeal configurations appear to be better encoded. These types of cues also have the advantage of being at least partially visually accessible in the case of vowels, through distinct degrees of openness and lip rounding. It should also be noted that Dimension 3 was associated with the quality of fricative production (LevelD values) as well as with the distinction between medial and posterior places of articulation. Children with CI were more strongly associated with a mode of fricative production characterized by energy concentrated in the mid frequencies (rather than in the high frequencies) and by a less marked distinction between fricative consonants relying on high-frequency spectral peaks. This performance profile also appears to be linked to the perceptual limitations of cochlear implants, particularly the technological difficulties in encoding frequencies above 8 kHz (Loizou, 2006), and is consistent with previous observations reported in CI users (Grandon & Vilain, 2020; Reidy et al., 2017; Yang & Xu, 2023).

Hierarchical classifications based on the factorial dimensions divided the sample into four distinct clusters. These clusters were clearly differentiated along Dimension 1 (linguistic performance) and Dimension 3 (oral/nasal contrast based on nasal resonance versus oropharyngeal configuration). Two sharply contrasting profiles were particularly salient: while Cluster 4, composed exclusively of TH children, displayed the highest linguistic performance, while Cluster 1, composed solely of children with CI, showed the lowest scores. These differences did not appear to be attributable to age: although children in Cluster 1 had a lower auditory age than those in Cluster 4, their mean auditory age was not statistically different from that of the CI children in Clusters 2 and 3, and even to that of the TH children in Cluster 2, yet without achieving comparable performance levels. These children, whose linguistic abilities remained markedly below those of peers with the same auditory age, may reflect atypical developmental profiles previously described in the literature (Benassi et al., 2021; Majorano et al., 2024) and/or contribute to the often-reported and difficult-to-explain variability observed among CI users.

Production profiles also differed markedly. The children in Cluster 4 clearly distinguished the oral/nasal contrast using typical mechanisms (oral vs. oro-nasal resonance; specific oral configuration), differentiated fricative places of articulation with rich spectral energy in mid- and high-frequency ranges, and produced a clear voiced/voiceless stop contrast in voice onset time (VOT). In contrast, the children in Cluster 1 displayed only weak marking of the oral/nasal opposition based on nasal resonance cues, without compensatory enhancement of the oropharyngeal configuration; the fricative places of articulation (high-frequency spectral peaks) were poorly differentiated, with friction noise predominantly concentrated in the mid-frequency range, and the VOT distinction between voiced and voiceless stops was reduced. This production profile directly reflects the transmission limitations inherent to cochlear implants, namely, the reduced spectral resolution in low frequencies (affecting the oral/nasal distinction) and degraded encoding of high frequencies (impacting fricative place and friction noise – Shadle et al., 2023).

Moreover, the children in Cluster 1 did not seem to compensate by relying more effectively on cues better encoded by the CI, such as temporal cues (VOT) or those related to oropharyngeal configuration (formant frequencies). These pronounced and weakly compensated perceptual difficulties, leading to underspecified phonological representations, are likely to cascade into broader linguistic weaknesses, as observed here, a link consistent with models connecting phonological representations to language development in developmental language disorders (Chiat, 2001; Joanisse & Seidenberg, 1998; Leonard et al., 1992), applied here to the perceptual limitations associated with CI use. Clusters 2 and 3, which included similar proportions of CI and TH children, presented intermediate profiles in linguistic performance. Cluster 2 outperformed Cluster 1 on all linguistic measures, whereas Cluster 3 differed from Cluster 4 only on more complex grammatical markers (reflexive pronouns, use of the imperfect tense). Acoustically, Clusters 2 and 3 diverged slightly: children in both groups showed a relatively balanced marking of the oral/nasal contrast between nasal resonance and oropharyngeal configuration. They also distinguished fricative places of articulation, but children in Cluster 3 displayed the highest levelD values, indicating lower energy concentration in the very high-frequency range of the friction noise.

A similar effect of auditory status was observed in both clusters: among CI children, marking through nasal resonance was weaker than in TH children, but marking through oropharyngeal configuration was stronger; moreover, levelD values were consistently lower (less high-frequency energy) among CI children. Thus, the CI subgroups in Clusters 2 and 3 appear to produce speech influenced by the implant's specific limitations (reduction in poorly transmitted cues: nasal resonance, high frequencies) but, unlike Cluster 1, they have developed effective compensatory strategies. Indeed, the over-marking of the oral/nasal contrast through oropharyngeal configuration has been associated with increased intelligibility (Fagniart et al., 2025a). Furthermore, the clear VOT distinction between voiced and voiceless stops reflects efficient use of temporal cues, which are known to be more reliably encoded by CIs. More broadly, efficient use of temporal cues among CI children has been linked to better spectral resolution (Landsberger et al., 2019) and improved identification/discrimination of oral and nasal vowels (Fagniart et al., 2024a), which could explain their superior performance compared to children in Cluster 1.

We sought to determine whether participant characteristics could account for their distribution across clusters. A chronological age effect emerged among the TH group: mean age increased progressively from Clusters 2 → 3 → 4, reflecting a maturation of linguistic abilities and phonetic mechanisms. The production profile of TH children in Cluster 3 was more unexpected: the older children in this group exhibited a lower representation of high-frequency energy in fricative noise and an over-marking of oropharyngeal configuration for the oral/nasal opposition. The presence of such a profile among TH children illustrates the high interindividual variability of productive abilities in the general population, without a major impact on linguistic development, as attested by the high-performance level of this group.

Among CI children, inter-cluster differences were not explained by either chronological or auditory age, which showed equivalent means. However, the age gap between CI and TH children varied across clusters, depending on whether chronological or auditory age was considered. For instance, in Clusters 2 and 3, CI children were chronologically older on average than their TH peers, but their mean auditory ages were equivalent to the chronological ages of TH children in Cluster 2. The intermediate performance of CI children in this Cluster could therefore be explained by a delayed exposure to the auditory signal through the CI, consistent with studies reporting equivalent performance between TH and CI children when matched for auditory age (Guo & Spencer, 2017). In this sense, CI children in Cluster 3 may represent a more favorable profile: despite having a mean auditory age lower than the chronological age of their TH peers in the same group, they exhibited advanced productive mechanisms (effective compensations) leading to high linguistic performance.

The various individual characteristics, and, for CI children, early implantation and exposure to CS, showed no statistical association with cluster distribution. Within our sample, it therefore appears that the development of compensatory strategies in response to perceptual difficulties may, or may not, emerge independently of multimodal stimulation via CS or of an early implantation profile. These findings contrast with studies highlighting the positive effects of early implantation (Karltorp et al., 2020; Kral et al., 2019) or exposure to CS (Leybaert et al., 2016; Machart et al., 2024; Van Bogaert et al., 2023). However, it is possible that our analyses—combining acoustic production data with diverse linguistic measures—capture greater interindividual variability than studies focusing on a single aspect. The combination of these dimensions reveals profiles that do not allow clear identification of favorable or unfavorable factors from a statistical perspective. However, although the statistical analyses did not reveal any significant association between individual variables and class membership, a descriptive examination of the children composing Cluster 1 provides some contextual elements. Among them, three were implanted after the age of two years, a condition often considered less favorable for language development in the literature (Karltorp et al., 2020; Kral et al., 2019; Sharma et al., 2020). Exposure to CS also appears limited in this group: two children are not exposed to CS and two others receive only occasional exposure. Finally, certain individual characteristics may also play a role, such as the presence of a bilingual environment for one child or unilateral implantation for another. Although these elements cannot be interpreted as explanatory factors in a statistical sense, they suggest that several potentially less favorable conditions may accumulate in some children presenting the most fragile linguistic profiles.

The one-year comparison within the CI subgroup revealed a general trend toward linguistic improvement (MLUm, reflexive pronouns, percentage of correct phonemes, naming, lexical diversity) and an enhancement in fricative quality (better mid/posterior distinction, higher ampDiff values). These developments may explain the shifts observed along the factorial dimensions when projected onto the initial model: toward positive values on D1 (improved linguistic skills) and toward negative values on D3, likely linked to the increased quality of fricatives, since cues related to nasal vowels did not change.

The fact that children progressed in distinguishing fricative places of articulation but not in nasal vowel resonance sheds light on the differential roles of spectral and articulatory constraints. Fine spectral resolution in the low-frequency range, critical for the oral/nasal distinction, is often imprecise with CIs (Başkent & Shannon, 2005), which could explain the initially variable levels and lack of consistent improvement. In contrast, the limitations in high frequencies for fricatives can be partially compensated through linguistic experience, via the use of somatosensory correlates and visual cues (e.g., visible labial differences depending on place of articulation). Multimodal development (maturation + experience) may therefore promote productive mastery of these contrasts despite perceptual limitations. The fact that only ampDiff (mid-frequency energy) and not levelD (very high-frequency energy) improved supports the persistence of constraints in the highest frequency ranges.

The new hierarchical classification resulted in few changes (4 out of 13 children). It is encouraging that one child from Cluster 1 moved to an intermediate cluster. This child was among the oldest in both auditory and chronological age (respectively 71 and 94 months old at T1) and lived in a bilingual environment (family language = Arabic). Family bilingualism is sometimes mentioned as a potential risk factor in deaf children (Vukkadala et al., 2018), although findings in CI populations remain nuanced (Deriaz et al., 2014; Van der Straten Waillet et al., 2023) and are strongly modulated by socioeconomic status, parental involvement, and the amount of oral stimulation in both languages. The transition of this child to Cluster 2, however, suggests a non-atypical developmental profile, likely to continue improving with maturation and experience.

Among the three other children who changed clusters, several favorable factors were observed: implantation before 16 months of age and early, sustained exposure to CS in two of them. Participant CI16 even reached a level allowing inclusion in Cluster 4, which initially consisted only of TH children with the highest linguistic proficiency. Nevertheless, 9 out of 13 children remained in the same cluster, reflecting progress that was insufficient to reach the levels of Clusters 3 and 4, despite increases in both chronological and auditory ages. This subgroup remained in Cluster 2, with a growing gap between their mean auditory age and the chronological mean of TH children in that same cluster at T1. This result supports the idea of a slower acquisition rate in CI children (Chilosi et al., 2013; Moreno-Torres et al., 2016), possibly linked to the cognitive cost of perceptuo-productive compensatory strategies, which may align their developmental trajectory with that of younger TH children (in both chronological and auditory terms).

All these results suggest several implications for clinical practice. In particular, it appears important to focus very early on the quality of the perception of certain phonological contrasts that are especially vulnerable when transmitted through the CI, such as the opposition between nasal and oral vowels, as well as on the impact that these difficulties may have on the development of linguistic skills, particularly at the morphemic level. Moreover, supporting effective visuo-perceptual strategies (e.g., CS) that may partially compensate for the perceptual limitations associated with the implant appears particularly relevant, as these strategies seem to be associated with linguistic profiles closer to those of typically hearing children. Finally, increased vigilance in follow-up appears necessary: although the acquisition of spoken language may approach that observed in typically hearing peers, it may nevertheless remain slower. This aspect becomes even more critical with increasing age, which is marked by greater learning complexity and an increased cognitive cost of linguistic processing.

This study opens many perspectives but also presents several important limitations that should be acknowledged: the modest sample size and the difficulties in achieving balanced groups (chronological and hearing age, age at implantation, etc.), which require caution in the interpretation of the results. In addition, the longitudinal dimension remains partial: only a fraction of the CI subgroup was retested, which does not allow the overall progression or that of each class as a whole to be evaluated and limits the analysis of influencing factors. Furthermore, additional data and a longitudinal approach for children in the TH group would also have been desirable. The age effects observed in this group should be interpreted with caution, as they rely on distinct age samples. Finally, it should be noted that the assessment protocol used in the present study was designed to be administered in a single session while remaining suitable for children across a broad age range (3–7 years). It therefore did not allow the evaluation of all linguistic abilities, particularly through perceptual tasks and/or a wider variety of production tasks. A nonword repetition task, for example, could be particularly relevant, as it allows the assessment of phonological production abilities without relying on internal lexical representations; such tasks have also shown good sensitivity in discriminating different performance profiles among children with cochlear implants (David et al., 2021). From this perspective, the replication of multivariate studies integrating both acoustic measures that objectify production strategies and broader measures of linguistic abilities, within a longitudinal framework and with more detailed documentation of the children's linguistic environment (notably, more precise characterization of exposure to Cued Speech and control of decoding skills, daily duration of implant use, etc.), would help consolidate these findings and deepen their interpretation, while also providing directions for improving diagnostic methods and the follow-up of children with cochlear implants.

CONCLUSION

The overall examination of phonological, lexical, and morphosyntactic performance, together with the acoustic analysis of the production of different phonetic segments, highlights a marked heterogeneity in the linguistic profiles of children with cochlear implants compared with their typically hearing peers. A first group of children shows difficulties across all the linguistic skills assessed, associated with production profiles consistent with significant perceptual limitations that are only weakly compensated. Two other groups display linguistic performance comparable to that of typically hearing children matched for hearing age. In these children, production profiles suggest the use of different compensatory strategies that help to partially overcome the perceptual constraints associated with the implant. Finally, the evolution of performance observed over a one-year interval reveals heterogeneous developmental trajectories, underscoring the importance of longitudinal monitoring of linguistic abilities in children with cochlear implants.

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The authors declare that they have no conflicts of interest related to this article.

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