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

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Abstract

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

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

1. Introduction

1.1. Speech sound production and cochlear implants

Cochlear implantation, by providing partial auditory input, can significantly improve oral language intelligibility. However, numerous studies on speech sound production have shown specificities compared to age-matched peers with typical hearing, especially for fricative segments among consonants. Warner-Czyz & Davis [1] studied consonant and vowel inventories and error patterns in a longitudinal study of young children with implants, compared with peers with typical hearing. Although production improved with age and CI use, consonants remained less accurate than vowels overall, with specific difficulties for children with CIs for fricative consonants. The authors suggest that the degraded auditory input provided by the implant may diminish the distinctiveness of fricative segments, carried by very high frequency ranges of lower intensity than vowels and less well encoded by the implant. This auditory-based theory is supported by various acoustic studies of fricative segment production. For example, studies showed less distinction in the /s/-/ʃ/ contrast [2,3,4], but also specificities in /f/-/s/ in French in French [5] as well as overall lower spectral values [6] in children with CI compared with typical-hearing peers of the same chronological and/or auditory age. However, it is noteworthy that some authors reach different conclusions regarding the developmental profile of children with CI. For example, Kim & Chin [7] observed error patterns in children with CI in terms of fortition errors (stopping of fricatives, devoicing) or lenition errors (fricativization of stops, voicing) typology in connection with Jakobson's markedness theory [8]. The prevalence observed in the study of fortition-type errors in children's development is consistent with the early phonological development stages of typically hearing children, suggesting a chronologically delayed acquisition profile but not specific to these children. Faes & Gillis [9] reach similar conclusions by noting that performance in the production of fricative consonants is delayed when comparing groups of children CI and typically hearing (TH) children in terms of age, but not when they are matched in terms of lexicon size. Considering these various studies and perspectives, it seems interesting to study the link between phonological production (with subjective analysis of the level of phonological accuracy and error patterns) and objective acoustic analysis of fricative segments among CI users. This constitutes the main objective of the present study.

1.2. Acoustic of fricative consonants

Fricative consonants are produced by the partial obstruction of airflow by the articulators, resulting in the generation of a noise source filtered by the shape of the vocal tract. Frication noise covers thereby a wide frequency and dynamic range that can vary over time [10]. The acoustic study of fricative segments is conventionally conducted through the measurement of spectral moments [11]. However, the values of spectral moments can vary depending on recording conditions and are highly dependent on analysis parameters [10]. Additionally, these values are often challenging to interpret in terms of effects related to the source or the filter [12], prompting the development of new measurement techniques. Various studies have validated the relevance of using spectral peak measured within mid-frequency range, as well as measurements of amplitude ratios (AmpDiff/AmpRange) and acoustic energy (levelD) between low/mid and mid/high-frequency ranges [10,12,13]. These measures allow the differentiation of various places of articulation for fricative consonants and distinguish voiced from voiceless fricatives. Voiced segments exhibit lower amplitudes in mid and high-frequency ranges compared to their voiceless counterparts [10]. These measurements are performed within spectra generated by the Multitaper Method (MTPS) [14], which averages a series of periodograms obtained

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through the collection of mutually orthogonal windows (tapers). The MTPS method is recognized for its reduced errors and higher temporal precision [15].

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

2. Method

2.1. Participants and task

The TH group consists of 47 French-speaking children with typical hearing, with an average age of 56±13m., without any learning delays or auditory disorders. The CI group is composed of 23 French-speaking children (mean age: 67±15m.) with congenital bilateral profound deafness and bilateral implants. Both groups were divided into three/four chronological age groups: 2;6-3;6 years (only for TH group), 3;7-4;6 years, 4;7-5;6 years, and 5;6-7 years (see table 1). For children in the CI group, auditory age groups were also formed, considering their age from the time of their first implantation.

Table 1: *Participants in each age subgroup*

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

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

2.2. Data processing and statistical analysis

All audio files underwent annotation by an initial examiner and were subsequently reviewed and corrected, if necessary, by the first author using Phon 3.1 software [16]. Inter-annotator agreement was high (> 90%). These annotations facilitated the extraction of the Percentage of Correct Phonemes (PCP), Correct Fricatives (PCF), and the identification of various types of production errors made by the children when there were discrepancies between the annotation and the target segment. Different types of errors involving fricatives were identified, including changes in manner of articulation (fricativization: stop to fricative; stopping: fricative to stop), changes in place of articulation, or substitutions between voiced and voiceless segments. The annotations were then exported to PRAAT [17] textgrid, with manual correction of the phoneme alignments. A script for automatic extraction of acoustic measures was subsequently employed for the analysis of the produced fricatives. The script extracts various measures at three temporal points: the beginning, middle, and end of the phoneme. For each temporal point, a multitaper power spectra (MTPS) [14] using 8 tapers was generated. Three acoustic measures were then collected from the generated spectra: spectral peak, levelD, and ampDiff for each target sibilant /s,z,ʃ,ʒ/ or ampRange for each target non-sibilant /f-v/. These measures require defining ranges for low, mid, and high frequencies within the spectrum. Given the absence of references for young children, we established these ranges through a meticulous analysis of the spectra, employing trial-and-error to identify parameters that most accurately represent our data. Finally, we adopted the values proposed by Shadle for adult females [10] with slight changes. Notably, we adjusted the maximum threshold for the mid-frequency range in the detection of spectral peaks for /s, z/ by elevating it to 10000 instead of 8000 and to 8000 instead of 4000 for /ʃ, ʒ/. The spectral peak was obtained by extracting the frequency of the amplitude peak in the mid frequencies, levelD was obtained calculating the difference in acoustic power between mid and high frequencies, and ampDiff the amplitude difference between low and mid frequencies. Precise definitions of these measures are provided in [10]. Linear generalized mixed models were conducted using the lme4 package (version 1.1-34) [18] in the R software [19], employing Gaussian regression for all metric variables derived from the acoustic analysis of all produced segments. For phonological analysis, percentages of correct phonemes (total, nasal vowels, fricatives, and stop consonants), as well as percentages of various types of errors observed, were calculated per subject to enable group comparisons. The models incorporated subject-related characteristics (auditory status, chronological/auditory age group), stimulus characteristics (fricative time point, fricative identity, place of articulation and voicing mode), and the interaction between these variables. To control inter-subject variability, a random intercept effect for the subject was included in the models. Significance testing for fixed effects were assessed using Chi-squared tests and corresponding p-values, conducted through the ANOVA function of the Car package [20] on the model. Pairwise comparisons between different levels of independent variables were also conducted using the emmeans package [21].

3. Results

3.1. Phonological analysis

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

3.2. Acoustical analysis

Figure 1 displays the values of various spectral measures and amplitudes within the TH and CI groups at three temporal points for the six target fricatives.

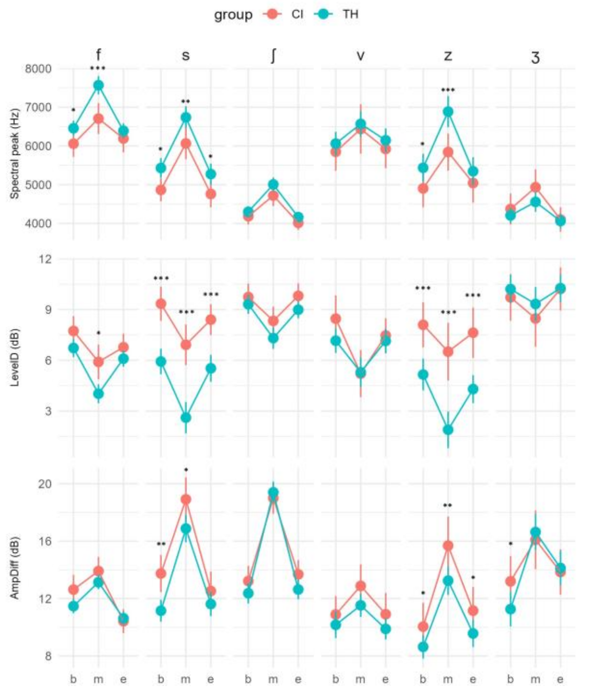

Figure 1: *Mean and confidence interval of the spectral peak (top graphs), levelD (middle) and AmpDiff (down) values for the TH (blue) and CI (red) groups for the 6 target fricatives at three segmental temporal points (b= beginning ; m = middle ; e = end of the fricative)*

Concerning spectral peak values, a group effect was observed, indicating lower spectral peak values in the CI group ($\chi2(1)$ = 9.4; p = 0.002). Additionally, there was a temporal point effect, showing higher values at the midpoint ($\chi2(2)$ = 337.5; p < 0.001). A significant interaction effect was found between group and phoneme type ($\chi2(5)$ = 23.9; p < 0.001), with group differences noted for the phonemes /f/, /s/, and /z/, and a group*temporal point interaction ($\chi2(10)$ = 40.4; p < 0.001) revealing a greater increase at the midpoint for the TH group. In the TH group, an effect of chronological age was observed ($\chi2(3)$ = 11.6; p = 0.008), with spectral peak values decreasing with age. An age*phoneme interaction effect ($\chi2(15)$ = 66.4; p < 0.001) revealed higher decreases for /f/ and /s/, resulting in improved distinction of articulation places among /f,s,ʃ/. Among voiced fricatives, /v/ and /z/ did not show distinction in terms of spectral peak values. In the CI group, no effect of chronological age was found. Instead, an interaction effect of auditory age group*phoneme ($\chi2(10)$ = 22.6; p = 0.01) was observed, with greater spectral peak value distinction in the older auditory age group for the voiceless /f, s, ʃ/ but not for the voiced /z, ʒ/, which were not distinguished.

Regarding the levelD values, a significant group effect is observed, with significantly higher values in the CI group ($\chi2(1)$ = 5.6; p =.01), along with a temporal point effect, indicating decreasing values at the midpoint ($\chi2(2)$ = 231.7; p < 0.001). A group*phoneme interaction effect ($\chi2(5)$ = 98.6; p < 0.001) is also noted, with values significantly higher for /f, s, and /z/ in the CI group. An interaction effect between chronological age group is observed in the CI group, demonstrating greater distinction between the three places of articulation for the voiceless /f, s, ʃ/ and the voiced /v, z, ʒ/, with values increasing with posteriority in the older group. A chronological age group effect is also noted in the TH group ($\chi2(3)$ = 14; p = 0.002), with significantly lower values in the younger children age group, and an interaction between age group and phoneme, with this decrease being significant for /s, ʃ, z/. A marginal voicing*group interaction ($\chi2(1)$ = 2.8; p = 0.09) was also found, with significant difference between voiced and voiceless levelD values in the TH group, but not in the CI group. A place of articulation*group interaction ($\chi2(1)$ = 89; p < .001) reveals that, in the TH group, /s,z/ has the lowest values, followed by /f,v/, and then /ʃ-ʒ/, whereas in the CI group, the order is /f,v/ < /s,z/ < /ʃ-ʒ/. AmpDiff values are marginally lower in TH group ($\chi2(1)$ = 3.5; p =.06) and a group*phoneme interaction effect is observed ($\chi2(1)$ = 14.1; p =.01) with significantly lower values for /s,z/ in the TH group. A time point effect is retrieved, with higher values for the midpoint ($\chi2(2)$ = 687.7; p <.001). In the TH group, a chronological age group effect was observed ($\chi2(3)$ = 16.6; p < .001) with significantly lower values in the younger age group and an age group*phoneme interaction ($\chi2(15)$ = 69.9; p < .001), indicating an increasing distinction between the three places of articulation in the older group. In the CI group, both chronological (age group effect) and auditory age group effects were found, leading to an increased distinction between the voiceless /f/ and /s, ʃ/ and the voiced /ʒ/ and /v, z/**.** It is noteworthy that the values of ampDiff are significantly lower for voiceless fricatives overall in both groups ($\chi2(1)$ = 73.7; p < .001), except for the /f-v/ pair in the CI group.

3.3. Correlation between phonological and acoustical data

The mean values per subject and per phoneme for each type of acoustic measure were compared to assess differences in articulation places (/f/-/s/, /s/-/ʃ/, /v/-/z/, /z/-/ ʒ/) and between voiceless (/f, /s, /ʃ/) and voiced (/v, /z, /ʒ/) fricatives. Correlations between these values and percentages of correct phonemes and fricatives, as well as various types of errors, were examined. A positive correlation was observed in both groups between the percentage of correct fricatives and the average spectral peak values difference between /z/ and /ʒ/ (r=0.52; p =.01; see figure 2). Additionally, positive correlations were found for /s/-/ʃ/ in the CI group (r=0.44; p=0.03) and the TH group for /v/-/ʒ/ (r=0.29; p=0.04). Mean differences in AmpdDiff between voiceless and voiced fricatives were also positively correlated with PCF in the CI group (r=0.42; p=0.05). In the CI group, the fricativization count is negatively correlated with spectral peak mean differences for /v-ʒ/ (r=-0.38; p=0.07), and stopping count is negatively correlated with spectral peak mean differences between /s/ and /ʃ/ (r=-0.45; p=0.03) and /z-ʒ/ (r=-0.53; p=0.009).

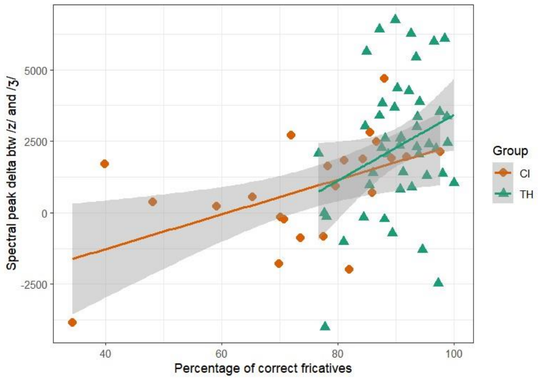

Figure 2: Correlations among TH and CI group between PCF and /z/-/ʒ/. spectral peak mean value differences.

4. Discussion

This research aimed to compare potential links between phonological performances and acoustic profiles of fricative consonant in children with CIs and their typically hearing peers. The first part of the analyses involved comparing the accuracy percentages of productions as judged by two listeners, as well as error patterns. Lower accuracy percentages, encompassing all phonemes, and lower percentages of correct fricatives were observed in the CI group. Examining the types of errors revealed specific error patterns in both groups, such as well-documented /s/-/ʃ/ substitutions and devoicings, considered classical errors in language development. Additionally, errors specific to the CI group were identified, including articulatory mode errors (fricativization, stopping) and voicing errors involving voiceless segments. While an effect of chronological age is observed on the percentage of total phonemes and correct fricatives in the TH group, along with a decrease in the number of devoicings and /s/-/ʃ/ substitutions, a chronological age effect is only found in the decrease of /s/-/ʃ/ substitutions in the CI group. The accuracy percentages and the number of other error types are not influenced by chronological or auditory age in the CI group. Although certain error patterns (stopping, devoicing) are consistent with Kim & Chin's [7] hypothesis of a similar but chronologically delayed development compared to typically hearing peers, the prevalence of certain atypical errors (fricativizations, voicing), and the fact that these different error types do not decrease with chronological/auditory age, seems more in line with the auditory-based hypothesis.

Acoustic analyses revealed overall lower spectral peak values in the CI group and especially for the phonemes /f/, /s/, and /z/. These lower values indicate more energy in the lower frequencies which can be associated with a longer anterior oral cavity, which may be related to a posteriorization of the constriction location and/or a more pronounced lip rounding. Sfakianaki et al. [14] obtained similar results for the phoneme /s/ in adults with hearing impairments (HI). The authors linked their results to Nicolaidis's study [22], in which a more pronounced posteriorization of the /s/ phoneme had been highlighted through electropalatography in adults with HI. However, it is noteworthy that the reduction of these values, although diminishing the distinction between the three places of articulation (/f-v/,/s-z/,/ʃ-ʒ/) compared to the TH group, does not result in a lesser distinction of these places of articulation according to our statistical analyses. The observed age effects indeed demonstrate that chronological age advancement in the TH group and auditory age in the CI group are associated with a greater distinction of /f-s-ʃ/. Conversely, /v-z/ in the TH group and /z-ʒ/ in the CI group didn't differ in the older age groups.

Children in the CI group also exhibit overall higher values of levelD and lower values for the AmpDiff measure. These two trends are consistent: children seem to show less reinforcement of amplitudes in mid-frequencies, leading to a decrease in AmpDiff values (differences between low and mid-frequencies), as well as less reinforcement in high frequencies, resulting in a higher levelD (ratio of mid to high frequencies). The reinforcement of mid and high-frequency spectral regions is associated with the strength of the noise source [10]; therefore, less reinforcement may be associated with a weaker constriction, resulting in less cancellation of the back-cavity resonances [12]. Also noteworthy is that these measurements can distinguish between voiced and voiceless phonemes, with the former marked by a weakening of acoustic energy. While the distinction between voiced and voiceless fricative phonemes is well pronounced in the TH group, evident in both levelD and AmpDiff values, the voicing effect is only found in the distinction between the pairs /s,z/ and /ʃ, ʒ/ within the AmpDiff values in the CI group.

All the acoustic characteristics observed in the CI group within our results appear entirely consistent with the limitations discussed in signal processing by the implant. Indeed, if the implant cannot accurately encode the entire high-frequency range, it may not be capable of transmitting relevant information to 1) distinguish between voiced and voiceless fricative segments and the appropriate degree of constriction; 2) capture higher frequency spectral peaks such as /f, v, s, z/, consequently impacting productive skills. These perceptual limitations, in addition to resulting in distinctive production characteristics, will have a direct impact on phonological development – a conclusion supported by the correlations we have identified. Notably, it has been observed that children in the CI group with better distinction of the /s-ʃ/ and /z-ʒ/ segments by spectral peak values, as well as voiced/voiceless segments by AmpDiff values, also had the highest percentage of correct fricatives and fewer errors in fricativization/occlusivication. This relationship appears consistent with the auditory-based hypothesis of the phonological difficulties of CI users. Moreover, it also highlights that the characteristic variability in the performance of children with CI could be associated with variability in the quality of the auditory signal coded by the implant (for a review, see [23]) and this interaction with the child's cognitive system's processing of the signal.

5. Conclusion

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

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