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Exposure to Canadian French Cued Speech improves consonant articulation in children with cochlear implants: acoustic and articulatory data

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ABSTRACT

Purpose: One of the strategies that can be used to support speech communication in deaf children is cued speech, a visual code in which manual gestures are used as additional phonological information to supplement the acoustic and labial speech information. Cued speech has been shown to improve speech perception and phonological skills. This exploratory study aims to assess whether and how cued speech reading proficiency may also have a beneficial effect on the acoustic and articulatory correlates of consonant production in children. **Method:** Eight children with cochlear implants (from 5 to 11 years) and with different receptive proficiency in Canadian French Cued Speech (three children with low receptive proficiency vs five children with high receptive proficiency) are compared to ten children with typical hearing (from 4 to 11 years) on their production of stop and fricative consonants. Articulation was assessed with ultrasound measurements. **Results:** The preliminary results reveal that cued speech proficiency seems to sustain the development of speech production in children with cochlear implants, and to improve their articulatory gestures, particularly for the place contrast in stops as well as fricatives. **Conclusion:** This work highlights the importance of studying objective data and comparing acoustic and articulatory measurements to better characterize speech production in children.

Key words: cochlear implants, cued speech, speech production in children, phonological development, consonant, acoustics, articulation, ultrasound

INTRODUCTION

With 34 million children worldwide suffering from a hearing loss of more than 35 decibels (dB)¹, the management of hearing impairment is a major public health issue. Without rehabilitation or support, hearing loss can have a detrimental impact on speech and language development which can affect communicative as well as cognitive abilities. Children with hearing loss may struggle in their social relationships and are at risk of delays in multiple cognitive functions (Lieu et al. 2020). This can have long-term educational and occupational outcomes. These repercussions also have an impact on behavior and socioemotional development, and have an adverse effect on quality of life and metacognitive aspects such as self-esteem, self-confidence, and self-construction (Hintermair, 2014).

As concerns auditory restoration, cochlear implants are now largely recommended for children with prelingual deafness. This remedial device is a surgically-implanted neuroprosthesis which provides sound perception by direct electrical stimulation of the auditory nerve. Although speech reception is partially restored, the perception of some acoustic features can be altered and oral language development may be adversely impacted by limited phonological skills (Bouton et al., 2012; Colin et al., 2017; Hansson et al., 2018; Leybaert & LaSasso, 2010; Nittrouer et al., 2018). This degraded phonological information may also have repercussions on the speech production of children with cochlear implants. It has been shown, for example, that French-speaking children with cochlear implants have difficulties in producing voicing contrasts (Grandon et al., 2017) and nasal contrasts (Bouton et al., 2012; Fagniard et al., 2020; Leybaert et al., 2016) as well as manner of articulation (Bouton et al., 2012; Leybaert et al., 2016), especially in fricatives (Grandon & Vilain, 2020), and place of articulation (Bouton et al., 2012; Grandon et al., 2017; Leybaert et al., 2016). These findings imply that additional support is needed to improve the perception and production of speech in children with cochlear implants. One of the strategies that can be used to support speech communication in deaf children is cued speech (Cornett, 1967). The aim of the present study is to investigate whether cued speech reading proficiency can contribute to improved articulation strategies in French-speaking children with cochlear implants.

Cued speech is a visual mode of communication that uses hand shapes and placements in combination with the mouth movements and speech to make the phonemes of spoken language look different from each other. In other words, manual gestures are used as additional visual cues to complement the degraded acoustic information as well as the labial information, which is necessarily limited. In this system, each consonant is cued with a specific handshape and each vowel is cued with a specific hand placement around the face (see Appendix 1 for Cued French²). The manual cue helps disambiguating phonemes which have similar lip shapes and can also indicate the

¹ According to the World Health Organisation (WHO) report, published in March 2021: <https://www.who.int/fr/news-room/fact-sheets/detail/deafness-and-hearing-loss>

² Although initially developed in English-speaking countries, cued speech has now been adapted to more than 60 spoken languages (Shull & Crain, 2010). Each of these spoken languages has its own cued speech system, adapted to its own phonological system (i.e. placements and configurations of the hand may therefore vary from one system to another). Since our study deals with the French language, we use the term Cued French when referring to the language manually cued for our participants. We restrict the use of the term cued speech to refer to the communication mode in general, without targeting a given language (see Fleetwood & Metzger, 1998 for more information)

presence of invisible phonemes like /k/ or /ʁ/, or invisible features such as voicing or nasality. For example, consonants /d/ and /n/, which differ in manner of articulation, are visually identical, as they both feature slightly parted lips, with the tip of the tongue barely visible behind the teeth. Different cued speech handshapes are used to introduce a contrast between these two consonants. In Cued French and Cued English, /n/ is produced with the addition of a handshape with all four fingers extended and the thumb hidden, whereas the production of /d/ is accompanied with a handshape with only the index finger raised. A manual cue is therefore provided for each phoneme in each word to convey spoken language (Shull & Crain, 2010), with or without phonation (LaSasso, 2010).

Communicating with a deaf child with added cued speech gestures is beneficial for the child's speech perception, as has been widely evidenced in a number of studies (e.g. for Cued Canadian English; Périer et al. (1990) for Cued French; Uchanski et al. (1994) for Cued American English), even without auditory information (Nicholls & Ling, 1982), with more benefits for earlier (Alegria et al., 1999) and longer duration of exposure to cued speech (Clarke & Ling, 1976; Périer et al., 1990). But a more remarkable consequence of receptive cued speech proficiency has also been demonstrated: children who have had intensive exposure to cued speech will eventually develop better abilities to process speech than their peers, even when cued speech gestures are absent. They become better at perceiving lip gestures only (Aparicio et al., 2012) or audio-only speech information (i.e. in the absence of cued speech gestures) (Kos et al., 2009), and at detecting phonological alterations in audiovisual speech (Van Bogaert et al. 2023). Moreover, children who have been exposed to cued speech have better phonological awareness, as revealed by rhyme judgment performance (Charlier & Leybaert, 2000 for Cued French) and rhyme generation skills (Paire-Ficout et al., 2003 and Leybaert et al., 2011 for Cued French; LaSasso et al., 2003 for Cued American English), with performance equivalent to their peers with typical hearing when cued speech exposure has been intensive. Such benefits have also been demonstrated for the specific population of children with cochlear implants (Cochard, 2003; Descourtieux et al., 1999; Hage & Leybaert, 2005; Bouton et al., 2011; Colin et al., 2017).

Based on these studies, it can be assumed that the improvement in speech perception and phonological awareness brought about by cued speech proficiency should be translated into an upturn in speech production skills. To our knowledge, the potential benefits of cued speech on speech production in children with cochlear implants have rarely been investigated. The studies of Vieu et al. (1998) and Kos et al. (2009) have shown that French-speaking individuals exposed to cued speech prior to cochlear implantation reached higher speech intelligibility scores than individuals exposed to other communication modes. In a more recent study, Machart et al. (2020, in prep) examined accuracy of phoneme production in French-speaking children with cochlear implants with high vs. low receptive cued speech proficiency. They showed that cued speech proficiency was related to improved production of voicing and nasal contrasts and of manner and place of articulation.

The long-term consequences of cued speech exposure on speech production abilities need to be further explored, as they are of crucial importance for the social and educational development of children with hearing impairment raised in a mainly oral environment. The present study provides an acoustic and articulatory investigation of the impact of cued speech proficiency on the speech production of children with cochlear implants.

Prior to the study by Machart et al. (2020, in prep), no data on speech production in children exposed to Cued French, or to another language, had been published (Gardiner-Walsh et al., 2021). Moreover, there are currently very few studies on the fine phonetic details of the speech production of children, especially those wearing cochlear implants. A few studies have used acoustic measurements to describe vowel and consonant development in children with cochlear implant. Concerning vowel production, Seifert et al. (2002) have used acoustic measurements to show that German or Swiss-German-speaking children who had received a cochlear implant before the age of four had better acoustic and articulatory control of their production than peers who had been implanted later. Conflicting opinions emerged from acoustic studies regarding the evolution of the acoustic vowel space after cochlear implantation (expansion of the vowel space: Hocevar-Boltezar et al., 2008, for Slovenian; Kunisue et al., 2006, for Japanese; no consistent change: Liker et al., 2007, for Croatian). This debate echoes the various, sometimes contradictory, acoustic and articulatory findings concerning speech motor development in children with typical hearing (Barbier et al., 2020; Ménard et al., 2020; Noiray et al., 2019; Zharkova, 2019). Acoustic measurements have revealed atypical production of nasal vowel contrasts in French-speaking children with cochlear implants (Fagniard et al., 2020). As concerns consonant production, acoustic studies have shown that sibilant fricatives, which are among the latest acquired consonants in typical development (MacLeod et al., 2011, among others), remain less accurate in American-English-speaking children with cochlear implants than in peers with typical hearing (Reidy et al., 2017). In addition, children with cochlear implants have difficulties in producing manner of articulation (Grandon & Vilain, 2020, for French) and place of articulation in fricative consonants (for French: Grandon, 2016; Grandon & Vilain, 2020; for Croatian: Mildner & Liker, 2008) as well as voicing contrasts in plosive consonants (for French: Grandon et al., 2017, for Croatian: Horga & Liker, 2006).

Very few studies have characterized the articulatory gestures produced by children in order to achieve a given acoustic-perceptual target. In one of the rare articulatory studies in children with cochlear implants using lingual ultrasound, Turgeon et al (2017) showed that English-speaking children with implants can produce contrasts in vowel places of articulation in the same way as their peers with typical hearing, although they show articulatory difficulties in producing vowel height contrasts. To our knowledge, no articulatory study has addressed the question of consonant production in children with cochlear implants.

Research question

The present study aims to investigate whether and how cued speech proficiency may improve speech articulation in French-speaking children with cochlear implants, even for consonants that are acquired late by children with typical hearing, such as sibilant fricatives. Speech production is assessed with acoustic and echographic articulatory measurements in two groups of children with cochlear implants, with high vs. low receptive cued speech proficiency, compared with a group of children with typical hearing. This comparison with typical variability helps to situate children with cochlear implants in relation to their typically developing peers. In addition, there are currently no ultrasound data in French on consonant production at this age, so these data will provide a baseline of place of articulation contrasts in children with typical speech development aged four to eleven years. This emphasizes the exploratory nature of this study, which provides original data to address both the lack of acoustic and articulatory data for the

analysis of consonants in French and the question of the effect of cued speech exposure on speech production.

Based on research findings on speech perception and production in children with cochlear implants, we outline a theoretical framework (Figure 1) to account for cued speech benefits in situations of auditory impairment. In this account, a cued speech education should help children with cochlear implants to develop fully specified phonological representations. These enriched phonological representations should sustain speech production abilities (i.e., articulatory gestures and acoustic outcomes).

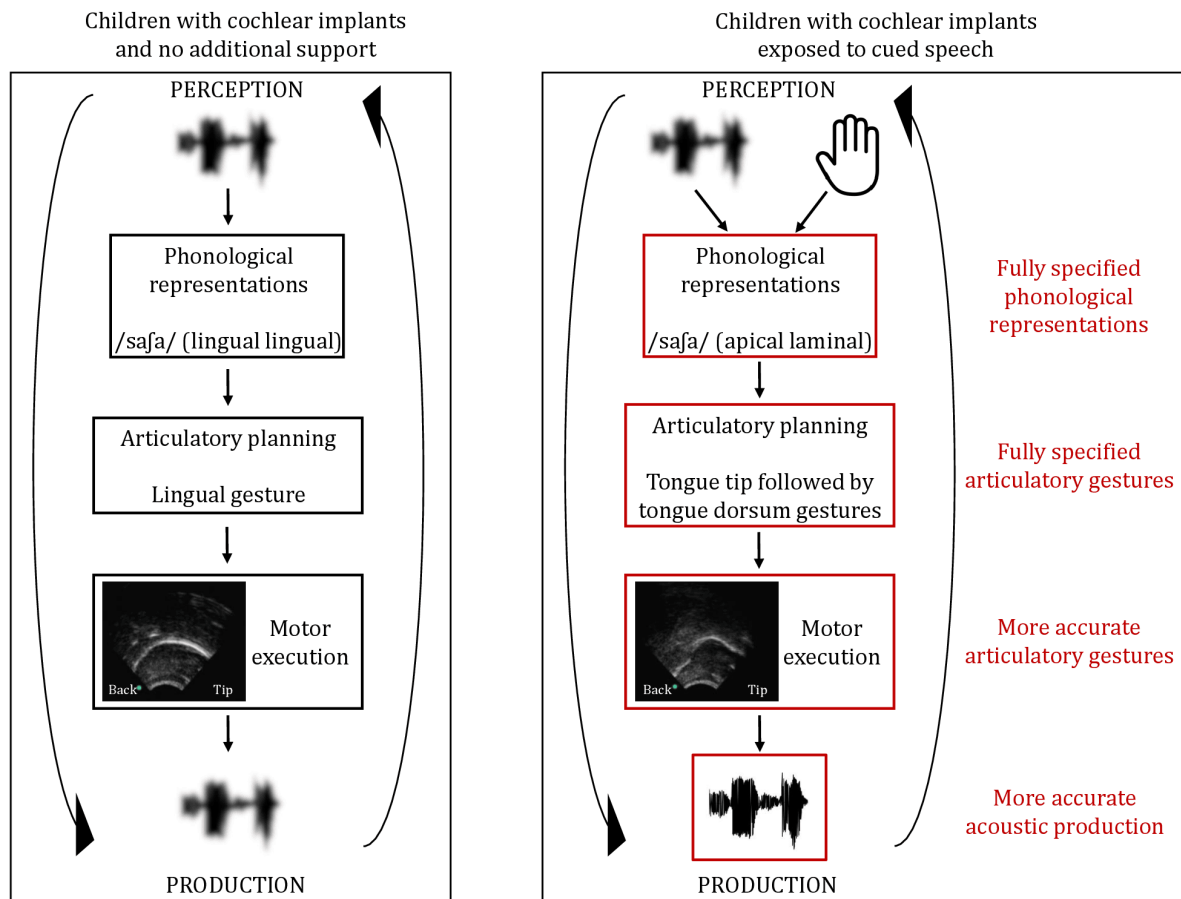


Figure 1: A theoretical account of cued speech benefits. The left panel illustrates the link between speech perception and speech production in children with cochlear implants who receive no additional support. The right panel presents the hypothesis that adding cued speech gestures results in enriched phonological representations.

To better quantify the influence of cued speech proficiency on articulatory precision, we focused on the stop consonants /t/ and /k/ and the sibilant fricatives /s/ and /ʃ/. These consonants, which can be distinguished by the horizontal position of the tongue (alveolar for /t/ and /s/, post-alveolar for /ʃ/, velar for /k/) and the vertical position of the tongue relative to the palate (occlusive contact with the palatal vault in /t/ and /k/ vs constriction in /s/ and /ʃ/), are among the most frequent phonemes substituted by children with cochlear implants (Machart et al., 2020). Furthermore, they involve phonological contrasts that are invisible, and are thus relevant to reveal the benefits of cued speech exposure. We predicted that the contrasts along the place of articulation feature in stops (represented by /t/ vs. /k/) and in later-acquired sibilant fricatives (represented by /s/ vs /ʃ/) should be greater in children with higher cued speech proficiency. More specifically, we expected articulatory representations to be

more specified in children with higher cued speech proficiency. We expected these enriched representations to be associated with more accurate articulatory gestures in terms of tongue position and configuration (tongue contour, highest point of the tongue and closest point of the tongue to the palate). We also expected more accurate acoustic realizations in terms of place of articulation (F2, F3 and center of gravity). Therefore, children with cochlear implants with a high level of cued speech proficiency were expected to display acoustic and articulatory productions similar to those of their peers with typical hearing. It is important to mention that the two targeted sibilant fricatives are among the latest acquired phonemes in children with typical hearing (Brosseau-Lapr e et al., 2018). As a result, the younger participants in the control group may themselves not yet produce them accurately. We investigated the benefit of cued speech exposure on the production of fricatives and examined whether high cued speech proficiency children with cochlear implants could display more accurate articulation than their hearing peers. In comparison, the productions of stops and fricatives by children with cochlear implants and no additional support were expected to be less accurate, due to under-specified phonological representations.

METHODS

Participants

Eight children with profound hearing loss fitted with cochlear implants and aged 65 to 133 months took part in this study (CI group) (age = 102.55 months, SD = 19.35). Hearing age was taken as the duration of implant use (i.e., the time elapsed since the first fitting with a cochlear implant), which appeared as a more informative and more comparable variable than the total duration of hearing device use. The mean duration of implant use was 64.60 months (SD = 29.66). The mean age at implantation was 37.96 months (SD = 19.27). All but one child had been implanted after 24 months (from 18 to 75 months). All the children in this group were recruited at Saint Jude School in Longueuil, Montreal, Quebec, where specialized teachers and Speech and Language Therapists (SLTs) used cued speech in its Canadian French version (Canadian French Cued Speech). All participants were monolingual and used oral language as a primary mode of communication and none of them had been exposed to Quebec Sign Language (LSQ). However, exposure to cued speech does not guarantee a high proficiency of receptive cue reading performance (Colin et al., 2015). For this reason, a cued speech reading level test (Appendix 2) was administered to the children by their SLTs, who classified them according to their cue reading skills. This is especially relevant as cue reading level³ has been shown to have an important role in speech production (Machart et al., 2020, in prep). Children were then split into two subgroups according to their cued speech proficiency. Participants in the CI- group had low cue reading skills, that is, they could at most decode a few familiar words at slow speed (level 4 of the scale, Appendix 2). This group consisted of three children including one girl from 65 to 133 months (age = 101 months, SD = 27.95). The mean duration of implant use was 68.60 months (SD = 29.61). The mean age at implantation was 32.40 months (SD = 16.02). All the children in the CI- group were fitted with two cochlear implants.

Participants in the CI+ group had high cue reading skills, that is, they could decode words and/or sentences at normal speed or a slightly reduced speed of speech (levels 1,

³ Cue reading level refers to the ability to “decode” manual keys

2 and 3 of the scale, Appendix 2). This group was composed of five children including five girls from 89 to 121 months (age = 103.55 months, SD = 10.85). The mean duration of implant use was 62.00 months (SD = 29.68). The mean age at implantation was 41.56 months (SD = 20.46). Three children in the CI+ group were fitted with two cochlear implants. The other two children were fitted with one cochlear implant and a hearing aid on the other ear. Demographics of the children with hearing impairment are presented in Table 1.

The CI group was compared with a group of 10 children with typical hearing (TH group) aged between 52 and 137 months (age = 96.25 months, SD = 25.68), including six girls. None of the typically hearing peers had ever been exposed to Canadian Cued French or LSQ. In this group, hearing age was simply defined as chronological age. All typically hearing children had detection thresholds better than 25 dB HL (decibel Hearing Level) at every frequency, which corresponds to typical hearing. None of them reported any speech disorder or had a learning disability or other known medical condition.

All participants (i.e., CI-, CI+ and TH) had Canadian French as their first language. Each child's parents, in each group of participants, gave written, informed consent in accordance with the Board of Ethics of Université du Québec à Montréal. Parents also completed a survey on their child's language development and background. This provided further individual and environmental information and allowed us to eliminate any associated disorder. Data were collected anonymously, according to GDPR regulations.

Speaker	Gender	Chronological age (in months)	Implantation age (in months)	Hearing age (in months)	Cued speech proficiency
005	F	65	18	47	CI-
004	M	102	54	48	CI-
003	M	133	24	109	CI-
007	F	89	75	14	CI+
009	F	102	24	78	CI+
010	F	102	27	75	CI+
001	F	103	49	54	CI+
006	F	121	24	97	CI+

Table 1: Demographics of children in the CI group

Materials and procedure

Speech production task: picture naming

In order to compare the precision of articulatory gestures in the three groups of children, speech production data were collected in two conditions. In the first condition, acoustic data were recorded without the ultrasound probe (*noUS* condition), in order to provide reference data to quantify the potential influence of the ultrasound probe on production. A second condition, presented here, consisted in recording the lingual movements using an ultrasound system (*US* condition). This study was pre-registered on Open Science Framework ([10.17605/OSF.IO/V8JAQ](https://osf.io/V8JAQ)). However, the present analysis deviates from our pre-registration in several points which are detailed in Appendix 3.

The corpus consisted of four words including one of the four targeted consonants /t/, /k/, /s/ or /ʃ/. The stimuli were simple words chosen for their frequency and imageability. All the words were disyllabic and included the target consonant in initial position and followed by vowel /a/, since word-initial consonants are usually produced with higher articulatory precision. This resulted in the following four French words:

“tapis” /tapi/ *carpet*, “carotte” /kɑʁɔt/ *carrot*, “sapin” /sapɛ̃/ *fir tree* and “chapeau” /ʃapo/ *hat*. To facilitate the detection of acoustic events such as burst onset in occlusive stops, all words were produced in a carrier sentence: “C’est les...” /sele.../ “*These are...*”. Each word was produced 6 times and prompted with 6 different pictures to make the task more pleasant to the children. A total of 36 tokens per condition (i.e. *noUS* vs *US*) allowed us to minimize fatigue while ensuring a sufficient number of repetitions. The order of the stimuli was randomized between participants and across conditions.

Phonological awareness test

As children start to learn reading, their phonological awareness skills change dramatically. During reading acquisition, children learn the correspondences between graphemes and phonemes, and phonological representations are restructured (Caudrelier et al., 2019). To situate our participants in their phonological awareness skills, a phonological awareness test was administered after the picture-naming task. This test consisted of a rhyme judgment task, a syllable deletion task in CVCV pseudo-words, and a phoneme deletion task in CVC. Children over 6 years also performed phoneme deletions in CCV (adapted from Caudrelier et al., 2019). The rhyme judgment task was taken from a French Canadian test for preschoolers (Lefebvre et al., 2008), while the other tasks were taken from BELEC (Mousty et al., 1994). When instructions were not understood by the participant, the task was not taken into account in the phonological awareness score. Several participants had difficulty understanding the instructions and fulfilling the syllable deletion task and the phoneme deletion tasks. We therefore chose to assess phonological awareness solely on the basis of the rhyme judgment task, which was performed by all the children. A linear model (*lm* function in package *stats* in R) showed a group effect with no effect of chronological age. Multiple comparisons revealed that CI- participants had lower phonological awareness scores than CI+ ($p = .019$) and TH ($p = .004$) groups. No effect of chronological age was observed, which means that the phonological awareness score is more explained by cued speech proficiency than by reading level in our groups.

Procedure

The child sat in front of a computer screen on which the pictures to be named were displayed. Simultaneous acoustic and ultrasound recordings of the target sentences were made. The acoustic signal was recorded using a high-quality Audio-Technica microphone (Omnidirectional condenser Headworn microphone, model number BP892). The SonoSite 180 Plus ultrasound system was used to synchronously record tongue displacement. This non-invasive technique has been shown to be very suitable for phonetic studies, since it provides a view of the global tongue contour in the mid-sagittal or coronal plane (Ménard et al., 2012; Ménard, Perrier, et al., 2013; Ménard et al., 2014). A 15-mm broadband (4–2 MHz) curved array transducer (with a field of view of 101 degrees) was used. The internal frame rate was 100 frames per second. The visual signal provided by the ultrasound and the audio signal were synchronized through a Panasonic AGDVX100 digital camera. As a result, the output frame rate of the ultrasound signal was 29.97 frames per second (standard NTSC frame rate). Acoustic and articulatory recordings of the child’s productions were synchronously recorded using a Blackmagic Intensity shuffle. The ultrasound system was placed on a table next to the child who wore a headset with an elastic band attached to hold the probe in position under his or her chin while allowing free movements of the jaw (Figure 2). One of the experimenters held the ultrasound probe, to ensure sufficient pressure for the detection of tongue movements

and also to make sure that the probe made contact with the chin (Figure 2). This protocol allowed the resulting tongue images to be in similar head-based coordination systems across all conditions. For all participants, the probe was positioned so that in the rest position, the largest tongue contour (from the root to the tip) could be seen on the image from the leftmost point to the rightmost point, despite the presence of the shadows of the jaw and the hyoid bone usually associated with ultrasound imaging. Visual inspection by the experimenter ensured that the occlusal planes were comparable across participants. Images were digitized using a digital camera at a rate of 29.97 images per second (standard NTSC rate).

The palatal vault is not entirely visible on echographic images of the tongue recorded with that method. In order to obtain reference data for the palate trace, children were asked to swallow a mouthful of water twice, after the picture-naming task. The horizontal placement of the palate trace is corrected for head movements. However, vertical placement could not be corrected for due to changes in probe height between recordings. Therefore, the palate trace is only used to locate the constriction and not to measure degree of constriction.

For the purpose of head movement correction, a mini video camera was also positioned in front of the child's mouth to record simultaneously the movement of the lips, of the head and of the ultrasound probe (see blue dots on Figure 2). To that end, nine adhesive blue markers (about 5 mm-diameter) were positioned on the participant's head and on the probe: three on the forehead, two on the upper and lower lips and four on the ultrasound probe.

An auditory screening test was completed with children with typical hearing to eliminate a possible hearing disorder (perception at 20 dB on the frequencies 250, 500, 1000, 2000, 4000 and 8000 Hz, using an Electronica 9910 audiometer).

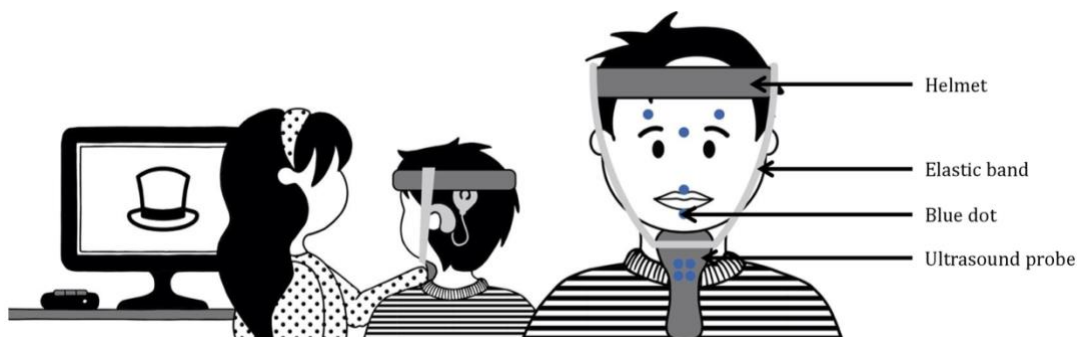


Figure 2: Set up of the experiment

Data processing

Acoustic data

All the items produced by the children were phonetically transcribed by an experienced phonetician and manually segmented and annotated on Praat (Boersma & Weenink, 2019). All the data were digitized at a rate of 44,000Hz but the acoustic signal was downsampled to 16,000 Hz to achieve more accurate formant detection in the [0, 6000 Hz] range. The beginning and the end of each target consonant were marked on an interval tier. To observe the ability of each group of participants to distinguish between places of articulation in stop consonants (i.e. /t/ and /k/) and in fricative consonants (i.e. /s/ and /ʃ/), we first extracted the formant values of F1, F2 and F3 at the end of the consonant (i.e., vowel onset). This allowed to capture the onset of the formant transition

from the consonant to the vowel. Since the subsequent vowel was always /a/, the formant values at vowel onset were sufficient to characterize the consonant place of articulation. Formants were extracted based on the Burg algorithm implemented in Praat. The window length varied from 0.015 to 0.020, with a pre-emphasis of 80. Likewise, formant values for stops (burst) and fricatives were measured using the Burg algorithm. Outlier values related to measurement errors were all corrected manually. Second, to better characterize the place of articulation in each fricative, the first spectral moment (i.e., mean center of gravity) was measured, based on a spectral analysis performed on a 40-ms window located at consonant mid-point. The mean difference between the centers of gravity of /s/ and /ʃ/ was also calculated for each group.

Articulatory data

Tongue contours were automatically extracted using the publicly available SLURP algorithm (Laporte, 2018; Laporte & Ménard, 2018), which is integrated into the tongue contour tracking program GetContours (Tiede, 2015) available under MATLAB. Several authors agreed that the SLURP algorithm allows an accurate and complete extraction of tongue contours from ultrasound images, over a large number of frames (Kabakoff et al., 2022; Whalen et al., 2019). Tongue contours for each stop consonant and each fricative consonant, by participant, are respectively available in Appendices 4 and 5.

For each tongue contour, three different articulatory measurements were extracted: (i) the Modified Curvature Index (MCI) values (Dawson et al., 2016), (ii) the front-back index, which refers to the x coordinate of the highest point of the tongue (Ménard, Toupin, et al., 2013) and (iii) the constriction place, which refers to the x coordinate at the closest point of the tongue to the palate (Ohkubo & Scobbie, 2019) were extracted, as illustrated in Figure 3. The difference between MCI values, between front-back indexes and between constriction places for each pair of consonants were also calculated for each group.

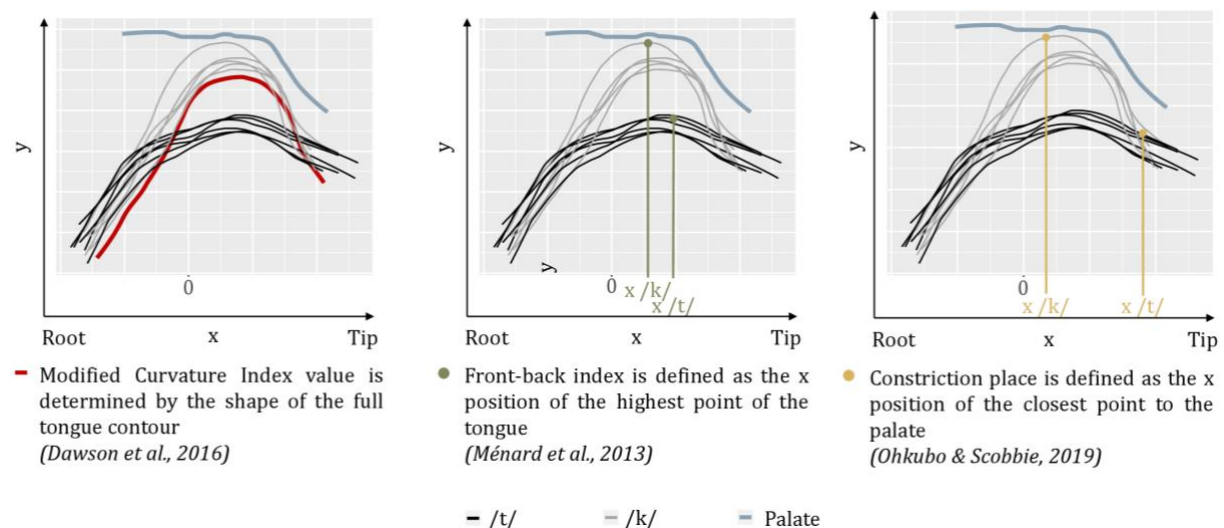


Figure 3: Articulatory measures used to analyze tongue contours

To ensure that all of our analyses were performed in the same plane, and to strengthen the reliability of our results, a head movement correction was performed prior to extraction of curvature values, highest point of the tongue and closest point to the palate. The nine blue dots placed on the participant's face and on the ultrasound probe (Figure 2) allowed measurement of the ultrasound probe displacement along the x- and

y- axes. Mm-based coordinates were then calculated with respect to the probe pixel-to-mm-ratio information, which resulted in a same coordinate system reference as tongue contours (Noiray et al., 2020).

Statistical analyses

All graphs and statistical analyses were done with the R software (R Development Core Team, 2012). Different types of statistical analysis methods were used in this study.

Phoneme accuracy

Phoneme accuracy was judged by an expert phonetician and only accurate productions were retained for acoustic and articulatory analysis, i.e. only productions that were judged “acceptable” realizations of the target phoneme (Appendix 4). It would not have made sense to compare the acoustic characteristics of substituted phonemes, e.g., if a /s/ target was realized as a /t/. A comparison of phoneme accuracy between groups was run using a backward step-wise variable selection with model comparisons to find the best-fitting linear model (*lm* function in R). The dependent variable was the mean number of correct realizations on all phonemes. Factors and interactions which did not improve model fit were excluded (*anova* function in R with a threshold of $p < .05$). Possible fixed-effect factors were Group and Chronological age or Hearing age.

One participant in the CI+ group did not produce any perceptually acceptable utterance for /t/ and was therefore not part of the statistical analysis for stops. One participant in the CI- group did not produce any /ʃ/ and was not part of the statistical analyses for the fricatives. One participant in the TH group was excluded from the statistical analyses for center of gravity in fricatives because interfering microphone noise prevented measurement in the high frequencies.

Acoustic and articulatory data

Linear mixed-effect models (*lme* function in R) were used to analyze F2 and F3 values, centers of gravity, MCI, x coordinates of the highest point of the tongue and x coordinates of the closest point of the tongue to the palate in stop and fricative production. A backward step-wise variable selection with model comparisons was applied to find the best-fitting model. First, all random-effect factors and fixed-effect factors of interest were included, alone and in interaction. Factors which did not improve model fit were then excluded (*anova* function in R with a threshold of $p < .05$). Possible fixed-effect factors were Group and Consonant (i.e. /t/ or /k/ for the stops and /s/ or /ʃ/ for the fricatives). Only Participant was introduced as a random-effect factor. When an interaction of factors was proven to be significant, multiple comparison tests were run, using the *glht* function in package *multcomp* in R.

Finally, linear models (*lm* function in package *stats* in R) were used to examine the difference between the centers of gravity of /s/ and /ʃ/, the difference between MCI measures in the two pairs of consonants, the difference between places of articulation of the highest point of the tongue and the difference between places of articulation of the closest point of the tongue to the palate. A backward step-wise variable selection with model comparisons was applied to find the best-fitting model. Factors and interactions which did not improve model fit were excluded (*anova* function in R with a threshold of $p < .05$). Possible fixed-effect factors were Group and Chronological_age or Hearing_age.

Statistical power

In order to assess the statistical power of the results, we followed the method described in Kumle et al. (2021), using a simulation-based approach, which is more flexible than an analytical power analysis. We simulated 10 000 data sets and, for each model, calculated the proportion of simulated data sets in which the selected model was similar to that obtained for the actual data. This proportion is the power estimate of the statistical analysis (i.e., percentage of cases in which the selected model is similar in the simulated data sets and in the actual data set). A power of 80% is commonly chosen as a threshold, but different thresholds may be more appropriate, particularly for exploratory studies (Kumle et al., 2021). For the purposes of this study, we assume that a power estimate of 80% or greater indicates a robust effect, that a power between 20% and 79% indicates that further data are required to conclude on the observed effect, and that a power below 20% does not allow us to conclude about the relevance of the measure studied.

RESULTS

Phoneme accuracy

The best-fitted linear model for the analysis of phoneme accuracy (full data in Appendix 4) only includes Group (i.e., CI-, CI+ and TH). Phoneme accuracy of children in the CI- group is significantly lower than that of their hearing peers ($p = .042$). Two participants (65 months and 133 months) anteriorized the production of /j/ and one participant (65 months) anteriorized the production of /t/. No differences between CI+ and TH groups nor CI+ and CI- groups were found. That is, children with cochlear implants and low cued speech proficiency produced less accurate phonemes than children with typical hearing. No effect of chronological age nor duration of implant use was observed.

Stop production

Acoustic data

- Effect of the ultrasound probe on the production

The best-fitted model for the analysis of the influence of the ultrasound probe on the production of stop consonant includes Group (i.e. CI-, CI+ and TH), Modality (i.e. without vs. with the ultrasound probe: *noUS* vs *US*) and Consonant (i.e. /t/ and /k/) as fixed-effect factors. Participant is included as a random-effect factor. A triple interaction is observed between Group, Modality and Consonant.

Figure 4 shows that an effect of Modality is observed in CI+ with lower F2 and F3 values in /k/ with the ultrasound probe than without (respectively $p < .001$ and $p = .007$). No effect of Modality is observed in CI- and TH for F2 and F3 values. Although an effect of the ultrasound probe is observed in CI+ children, the distinction between places of articulation in stops is not altered. Formant values are lower with the addition of the ultrasound probe but the perturbation of the jaw does not interfere with the distinction between places of articulation.

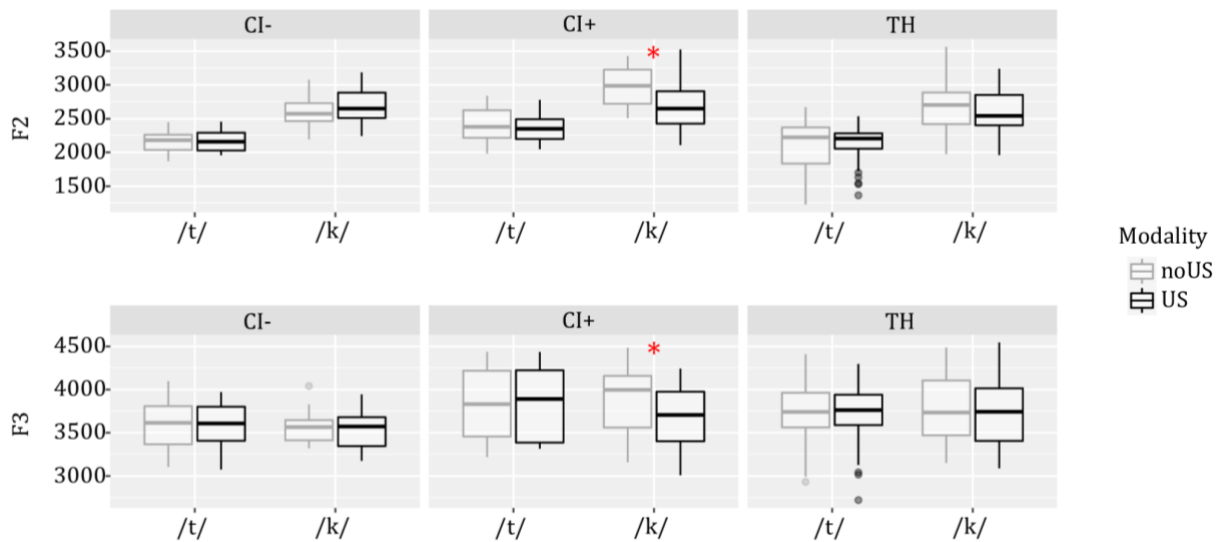


Figure 4: Difference between the two conditions (without the ultrasound probe in grey, and with the ultrasound probe in black). Mean of F2 is given in the upper panel and mean of F3 is given in the bottom panel. Red stars indicate a significant difference.

- F2

The best-fitted model for the analysis of F2 in stop production only includes Consonant (i.e. /t/ and /k/) as a fixed-effect factor. Participant is included as a random-effect factor. CI-, CI+ and TH produce a significantly lower F2 in /t/ than in /k/ ($p < .001$) (Figure 5, middle panel). The statistical power estimate for the F2 feature is robust at 84.3%. In other words, F2 values appear to be a relevant index of stop consonant place of articulation in children.

- F3

The best-fitted model for the analysis of F3 in stop production does not include any fixed-effect factor (Figure 5, right panel). Neither effect of Group or Consonant are observed: CI-, CI+ and TH do not distinguish between stops according to F3. The statistical power estimate for the F3 feature is also robust at 83.7%. In other words, F3 feature does not seem to be a relevant index of stop consonant place of articulation in children.

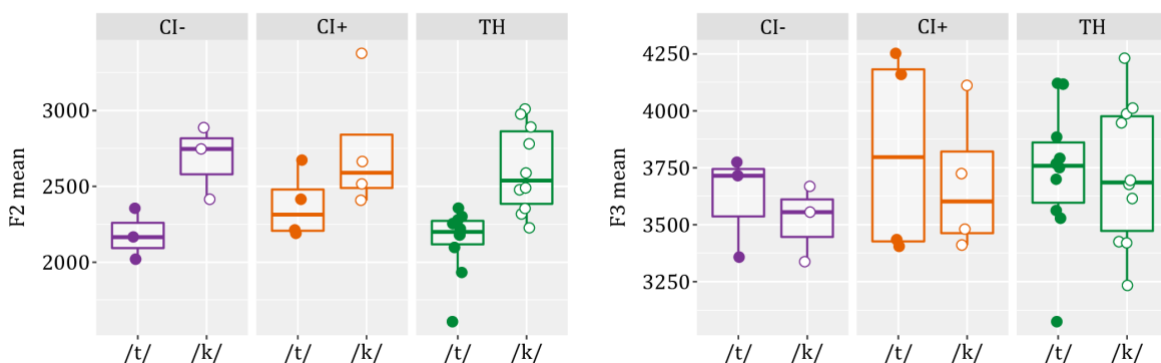


Figure 5: Mean F2 (left panel) and F3 (right panel) for each stop consonant (/t/ solid circle, and /k/ open circle) by group (CI- in purple, CI+ in orange and TH in green). Each dot corresponds to the mean formant value for one given consonant for each participant.

Articulatory data

- MCI

The best-fitted model for the analysis of MCI in stop production includes Group (i.e. CI-, CI+ and TH) and Consonant (i.e. /t/ and /k/) as fixed-effect factors. Participant is included as a random-effect factor. An interaction is observed between Group and Consonant. Multiple comparison tests reveal a significant effect of Consonant (Figure 6a, left panel): CI-, CI+ and TH show a significantly lower MCI in /t/ than in /k/ (respectively $p = .010$, $p < .001$ and $p < .001$). No significant difference is observed between groups for any of the two stops. The statistical power estimate for the MCI feature is 40.8%. That is, MCI values might be relevant for the articulatory analysis of stop consonant place of articulation in children but more participants are needed to confirm these results.

- Contrast between MCI values

The best-fitted model for the analyses of the difference between MCI values of the stop consonants /t/ and /k/ only includes Group (Figure 6a, right panel). CI- show a slightly lower difference than that of TH ($p = .081$). The difference between MCI values in CI+ is not significantly different from that of TH. No difference is observed between CI- and CI+.

- Front-back index

The best-fitted model for the analysis of the front-back index of the highest point of the tongue in stop production only includes Consonant (i.e. /t/ and /k/) as a fixed-effect factor. Participant is included as a random-effect factor. CI-, CI+ and TH distinguish significantly between places of articulation in /t/ and /k/ ($p = .002$), with a more anterior articulation in /t/ (Figure 6b, left panel). The statistical power estimate for the front-back index feature is 57.2%. As for the MCI feature, more participants are needed to confirm the relevance of the front-back index measurement for the articulatory analysis of stop consonant place of articulation in children.

- Contrast between front-back index

The best-fitted model for the analysis of the contrast between front-back index of the highest point of the tongue for the two stops does not include any fixed-effect factor (Figure 6b, right panel). Neither Group nor Consonant effects are observed.

- Constriction place

The best-fitted model for the analysis of the place of the constriction in stop production only includes Consonant (i.e. /t/ and /k/) as a fixed-effect factor. Participant is included as a random-effect factor. CI-, CI+ and TH distinguish significantly between places of articulation in /t/ and /k/ ($p < .001$), with a more anterior articulation in /t/ (Figure 6c, left panel). The statistical power estimate for the constriction place feature is 2.9%. This very low statistical power indicates that the constriction place feature may not be relevant for the analysis of stop consonant place of articulation in children.

- Contrast between constriction places

The best-fitted model for the analysis of the contrast between constriction places in stop production does not include any fixed-effect factor (Figure 6c, right panel). Neither Group nor Consonant effect are observed.

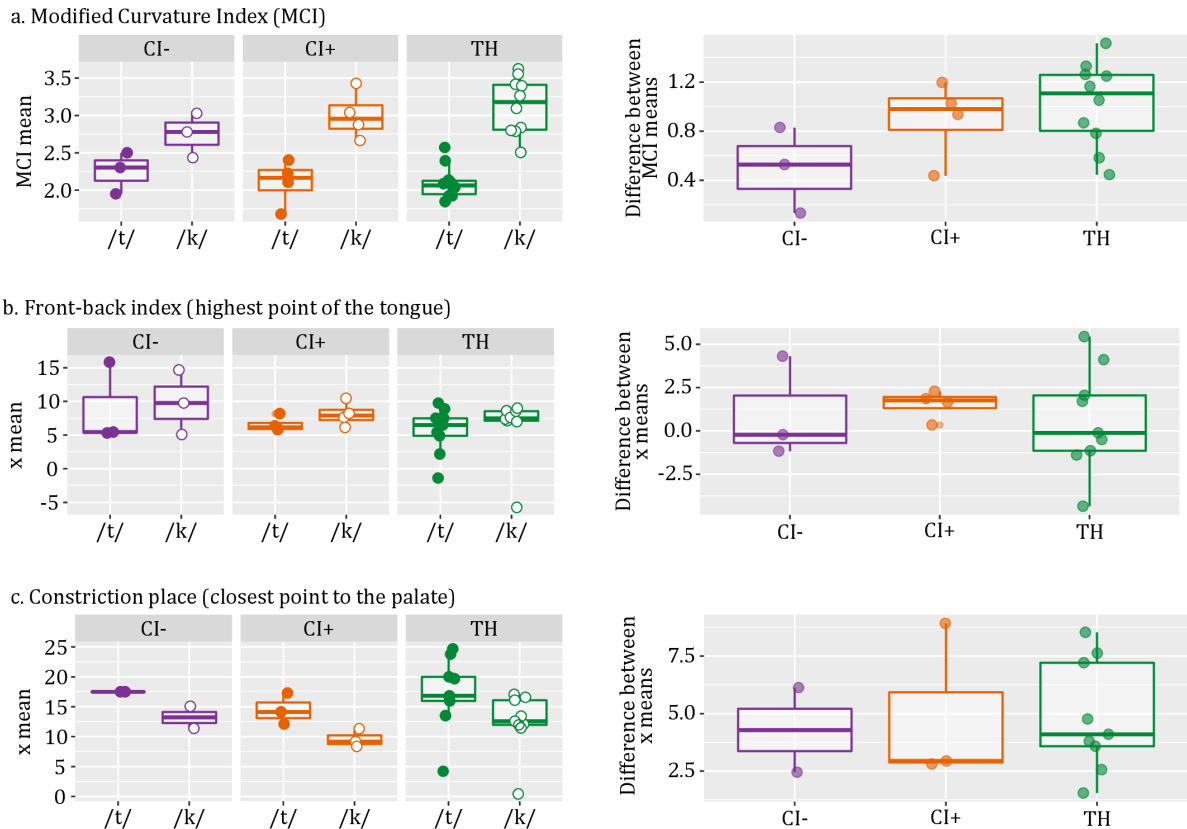


Figure 6: Modified curvature index (upper panel), mean x position of the highest point of the tongue (middle panel) and mean x position of the constriction place (bottom panel) for each stop consonant (/t/ solid circle, and /k/ open circle) by group (CI- in purple, CI+ in orange, and TH in green). Distributions are illustrated by boxplots in the left panel. Contrasts between means are illustrated in the right panel.

Fricative production

Acoustic data

- Effect of the ultrasound probe on the production

The best-fitted model for the analysis of the influence of the ultrasound probe on the production of fricative consonant includes Group (i.e. CI-, CI+ and TH), Modality (i.e. noUS and US) and Consonant (i.e. /s/ and /ʃ/) as fixed-effect factors. Participant is included as a random-effect factor. A triple interaction is observed between Group, Modality and Consonant.

Figure 7 shows that an effect of Modality is observed in CI+ with slightly lower F2 values in /s/ ($p = .052$) and higher F3 values in /ʃ/ ($p = .032$) with the ultrasound probe than without. An effect of Modality is also observed in TH with lower F2 values with the ultrasound probe than without in both fricatives ($p < .001$). An effect of Modality is finally observed in CI- with lower F3 values in /ʃ/ ($p = .018$) and lower centers of gravity in /s/ ($p = .026$) with the ultrasound probe than without. No other effect of Modality is observed. However, as for stop consonants, this perturbation due to the ultrasound probe does not interfere with the distinction between places of articulation in fricative consonants.

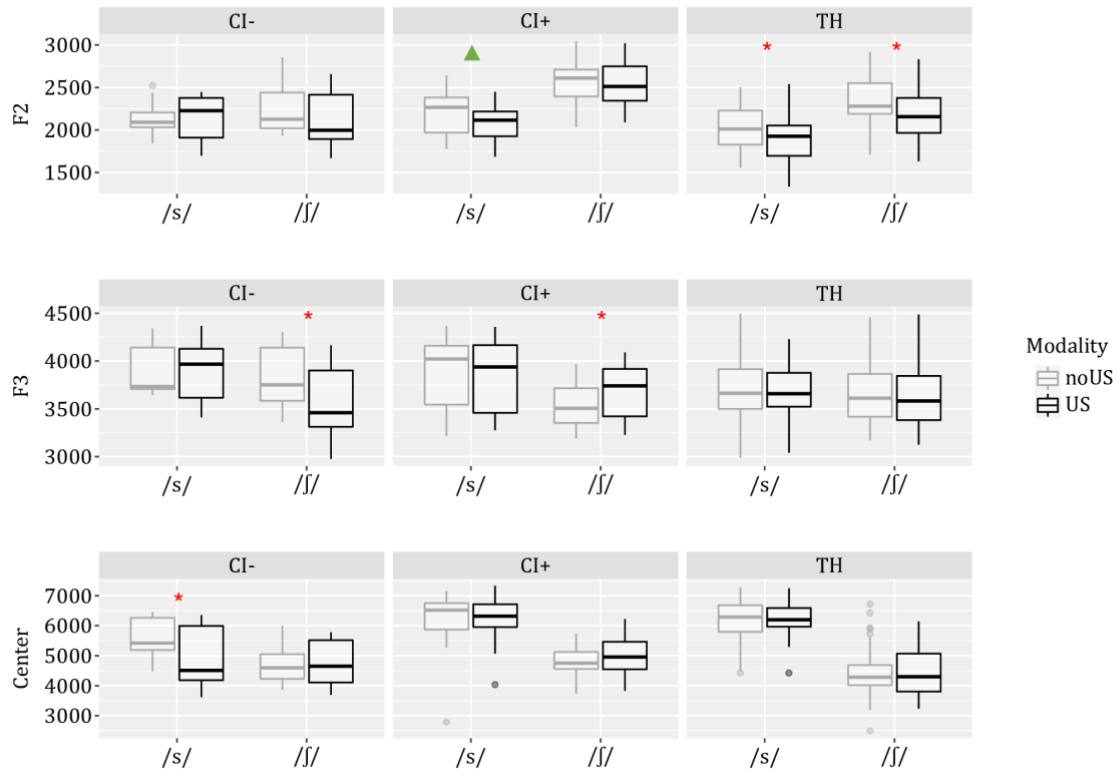


Figure 7: Difference between the two conditions (without the ultrasound probe in grey, and with the ultrasound probe in black). Mean of F2 is given in the first panel, mean of F3 is given in the second panel and mean of center of gravity is given in the third panel. Red stars indicate a significant difference whereas green triangles indicate a slight difference.

- F2

The best-fitted model for the analysis of F2 in fricative production includes Group (i.e. CI-, CI+ and TH) and Consonant (i.e. /s/ and /ʃ/) as fixed-effect factors. Participant is included as a random-effect factor. An interaction is observed between Group and Consonant. Multiple comparison tests reveal a significant effect for consonant in the CI+ group (Figure 8, upper middle panel): CI+ and TH produce a significantly lower F2 in /s/ than in /ʃ/ ($p < .001$) whereas CI- do not seem to distinguish between both fricatives. An effect of Group is also observed for /ʃ/ between CI+ and TH ($p = .020$), with a significantly higher F2 in CI+. The statistical power estimate for the F2 feature is 22.6%. The measurement of F2 values at consonant offset seems less relevant for the analysis of fricative consonants than it is for stop consonants in children. More data are needed to confirm the relevance of this feature for the analysis of the acoustic correlates of fricative consonants.

- F3

The best-fitted model for the analysis of F3 in fricative production includes Group (i.e. CI-, CI+ and TH) and Consonant (i.e. /s/ and /ʃ/) as fixed-effect factors. Participant is included as a random-effect factor. An interaction is observed between Group and Consonant. Multiple comparison tests reveal a significant effect for the consonant (Figure 8, upper right panel): CI- and CI+ produce a significantly higher F3 in /s/ than in /ʃ/ (respectively $p = .004$, and $p = .011$) whereas TH do not seem to distinguish between the two fricatives. No significant difference is observed between groups for any of the two fricatives.

The statistical power estimate for the F3 feature is 24.7%. As for F2 values, F3 at consonant offset seems less relevant for the analysis of fricative consonants than it is for stop consonants in children.

- Center of gravity

The best-fitted model for the analysis of center of gravity in fricative production includes Group (i.e. CI-, CI+ and TH) and Consonant (i.e. /s/ and /ʃ/) as fixed-effect factors. Participant is included as a random-effect factor. An interaction is observed between Group and Consonant.

Multiple comparison tests reveal a significant effect for consonant in the CI+ and the TH groups (Figure 8, bottom left panel): CI+ and TH produce a significantly higher center of gravity in /s/ than in /ʃ/ ($p < .001$) whereas CI- do not seem to distinguish significantly between the two fricatives. A significant effect of Group is also observed for /s/ between CI- and CI+ ($p = .005$) and between CI- and TH ($p = .003$), with a lower center of gravity in CI-. A slight effect of Group is also observed for /ʃ/ between CI+ and TH ($p = .099$), with a higher center of gravity in CI+.

The statistical power estimate for the center of gravity feature is 94.7%, suggesting high reliability of center of gravity measurements in the analysis of fricative production in children.

- Contrast between centers of gravity

The best-fitted model for the analyses of the contrast between centers of gravity in the fricative consonants /s/ and /ʃ/ only includes Group. CI- show a significantly lower difference than that of TH ($p = .013$). No difference is observed between CI- and CI+ or CI+ and TH (Figure 8, bottom right panel).

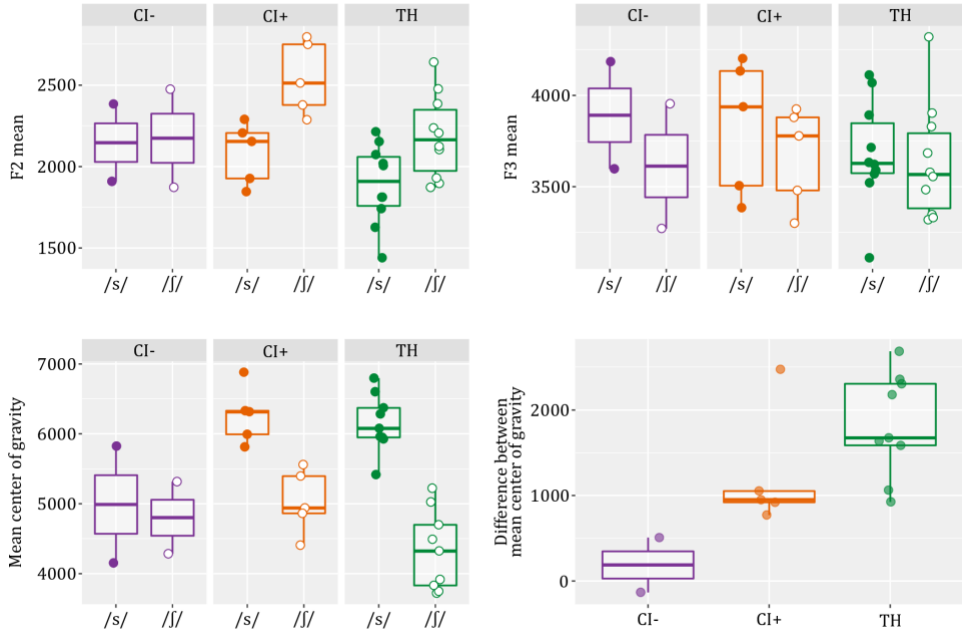


Figure 8: Mean F2 and F3 (upper panel) and mean center of gravity (bottom panel) for each fricative consonant (/s/ solid circle, and /ʃ/ open circle) by group (CI- in purple, CI+ in orange, and TH in green). Distributions are illustrated by boxplots in the upper panel and in the bottom left panel. Contrasts between mean centers are illustrated in the bottom right panel. Each dot corresponds to the mean value for one given consonant for each participant.

Articulatory data

- MCI

The best-fitted model for the analysis of MCI in fricative production only includes Consonant (i.e. /s/ and /ʃ/) as fixed-effect factors. Participant is included as a random-effect factor. CI-, CI+ and TH show a significantly lower MCI in /s/ than in /ʃ/ ($p < .001$) (Figure 9a, left panel). The statistical power estimate for the MCI feature is 63.8%. As for stop consonants, more participants are needed to confirm the relevance of the MCI feature for the articulatory analysis of sibilant fricative place of articulation in children.

- Contrast between MCI values

The best-fitted model for the analysis of the contrast between MCI values in fricative production does not include any fixed-effect factor (Figure 9a, right panel). Neither effect of Group or Consonant are observed.

- Front-back index

The best-fitted model for the analysis of the front-back index the highest point of the tongue in fricative production includes Group (i.e. CI-, CI+ and TH) and Consonant (i.e. /s/ and /ʃ/) as fixed-effect factors. Participant is included as a random-effect factor. An interaction is observed between Group and Consonant.

Multiple comparison tests reveal a significant effect of Consonant in the CI+ group (Figure 9b, left panel): CI+ distinguish significantly between places of articulation in /s/ and /ʃ/ ($p < .001$), with a more anterior articulation in /s/ than in /ʃ/, whereas CI- and TH do not seem to distinguish significantly between the two fricatives. No significant difference is observed between groups for any of the two fricatives.

The statistical power estimate for the front-back index feature is 3%. This very low statistical power suggests that the front-back index feature might not be relevant enough for the analysis of fricative consonant place of articulation in children.

- Contrast between front-back index

The best-fitted model for the analyses of the contrast between front-back index of the highest point of the tongue in fricative consonants /s/ and /ʃ/ only includes Group (Figure 9b, right panel). CI+ show a slightly higher difference than that of TH ($p = .058$). No difference is observed between CI- and CI+ or CI+ and TH.

- Constriction place

The best-fitted model for the analysis of the place of the constriction in fricative production only includes Consonant (i.e. /s/ and /ʃ/) as a fixed-effect factor. Participant is included as a random-effect factor. CI-, CI+ and TH distinguish significantly between places of articulation in /s/ and /ʃ/ ($p < .001$), with a more anterior articulation in /s/ than in /ʃ/ (Figure 9c, left panel). The statistical power estimate for the constriction place feature was 2.5%. As for stop consonants, this very low statistical power indicates that the constriction place feature may not be relevant for the articulatory analysis of fricative consonant place of articulation in children.

- Contrast between constriction places

The best-fitted model for the analysis of the contrast between constriction places in fricative production does not include any fixed-effect factor (Figure 9c, right panel). Neither effect of Group or Consonant are observed.

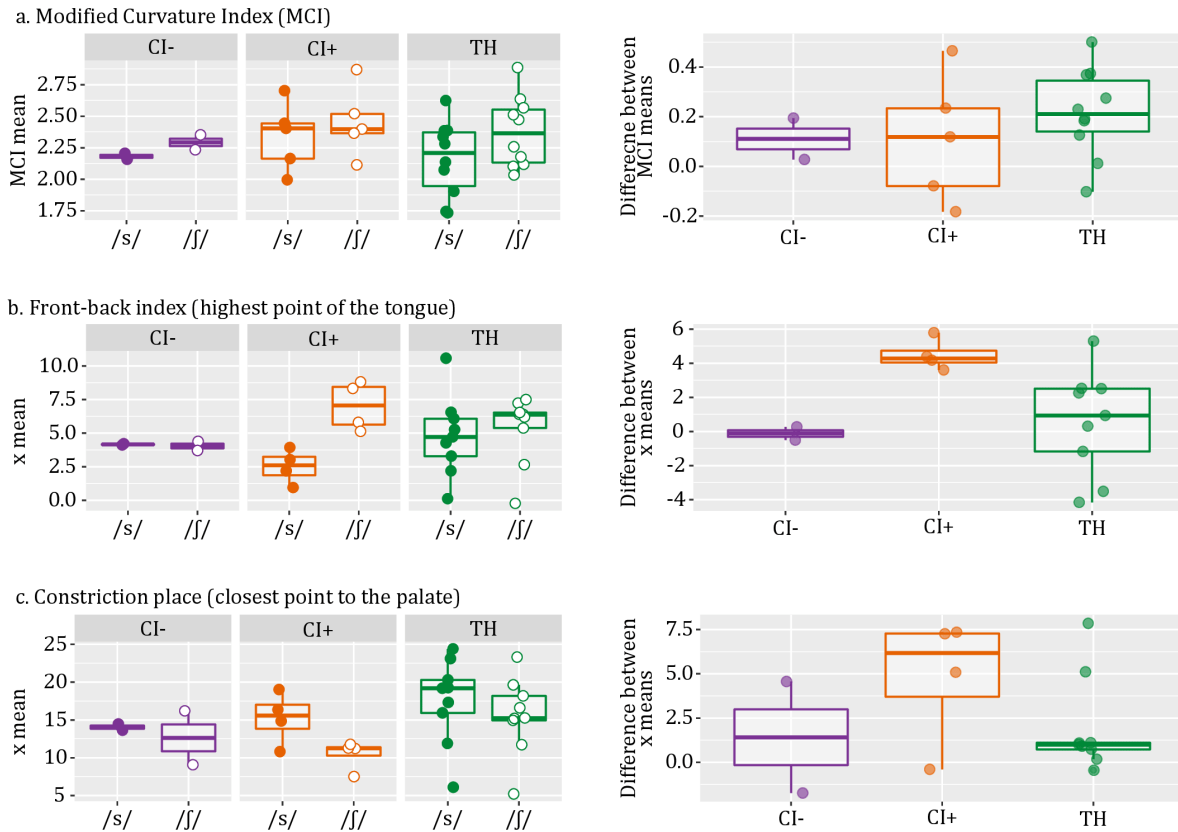


Figure 9: Modified curvature index (upper panel), mean x position of the highest point of the tongue (middle panel) and mean x position of the constriction place (bottom panel) for each fricative consonant (/s/ solid circle, and /ʃ/ open circle) by group (CI- in purple, CI+ in orange, and TH in green). Distributions are illustrated by boxplots in the left panel. Contrasts between means are illustrated in the right panel.

DISCUSSION

A first objective of this exploratory study was to observe whether and how cued speech proficiency may improve speech articulation in French-speaking children with cochlear implants. A second objective was to provide objective data on consonant production in French-speaking children, with or without hearing impairment. To this aim, acoustic and articulatory data were recorded in two groups of children with cochlear implants with high (CI+) vs. low (CI-) receptive cued speech proficiency and a group of children with typical hearing (TH). Acoustic measurements consisted in formant values at consonant offset for the stop consonants /t/ and /k/ and in formant values at consonant offset and center of gravity for fricatives /s/ and /ʃ/. Articulatory measurements consisted in the Modified Curvature Index, the front-back index of the highest point of the tongue, and the place of constriction. The analysis focused on contrasts along the place of articulation feature in stops and in sibilant fricatives. The impact of cued speech proficiency on the production of these contrasts was examined by comparing acoustic and articulatory productions in the three groups of children.

Consonant production

Stops

As concerns the acoustics of stop consonants, the significant differences found were that the F2 values at consonant offset were lower for /t/ than for /k/, and that the

F3 values were equal for the two places of articulation for all three groups of children. Statistical power for these two features was high enough to confirm the reliability of the results. These data differ from typical adult formant patterns for these places of articulation. Adults' alveolars typically have higher F3 values than velars, whereas F2 values tend to be similar for both places of articulation (Schwartz et al., 2012). As concerns F2 and F3 patterns, the differences between children and adults could be attributable to the fact that the back cavity (behind the constriction) is smaller in children, especially relatively to the front cavity. This difference in relative cavity size could result in different relations between cavity resonance frequencies (Ménard et al., 2004). In the future, this hypothesis should be tested, for instance with simulations using an articulatory model of the growing vocal tract (see e.g. Ménard et al., 2007). In sum, our three groups of children produce a significant distinction between the places of articulation for the alveolar /t/ and the velar /k/ stops. Moreover, they seem to produce these places of articulation in the same way, since no group effect was found.

Regarding articulatory data, MCI values only differed according to stop place of articulation, with no group effect, suggesting that all groups produced a more complex curvature in velar than alveolar stops (see Appendix 5). However, when the contrast between the MCI values for the two places of articulation was considered, a group effect appeared. A lower contrast was observed in the CI- group, indicating a reduced distinction between consonants in these children as compared to the other two groups. This result suggests that children with cochlear implants and low receptive cued speech proficiency might be less able to produce distinctive tongue shapes for alveolar and velar stops than the other children. High receptive cued speech proficiency might allow children with cochlear implants to adjust tongue curvature to better differentiate between stop consonants and to reach productions similar to those of peers with typical hearing. However, the statistical power for this feature is low, which means that no conclusion about the relevance of this measurement can be drawn for now. This could be related to the small sample size or to the irrelevance of this measurement. More data are needed to confirm any effect. A second articulatory feature examined was the horizontal position of the highest point of the tongue. A consonant effect was found, which means that all three groups distinguished between alveolar and velar stops on the front-back feature. As expected, the tongue was in a more anterior position for the alveolar than for the velar stop. There was no group effect for this feature, which means that children in the three groups produced alveolar and velar stops in the same way. As for the MCI feature, the statistical power of the front-back index is low. No conclusion can therefore be drawn, but a trend can be observed, suggesting a benefit of Canadian Cued Speech proficiency on articulatory gestures in stop consonants, which will need to be confirmed with more data. Finally, the third articulatory parameter was the place of constriction, measured as the closest point of the tongue to the palate. Once again, a consonant effect was found, meaning that children produced a distinction along that parameter, whereas the absence of a group effect showed that all groups produced the constriction place contrast in the same way. The statistical power of this feature is very low, suggesting that the measurement of constriction place may not be relevant for the analysis of the place of articulation of stop consonants in children.

Fricatives

Concerning the acoustic correlates of fricative consonants /s/ and /ʃ/, children with typical hearing distinguished between the alveolar and postalveolar places of articulation. The formant patterns observed were consistent with those obtained in stops.

Lower F2 values were obtained for the more anterior place of articulation, i.e. for /s/ than for /ʃ/, whereas F3 was similar in the two consonants. Therefore, as observed for stops, the best acoustic correlate of fricative place of articulation in children with typical hearing seems to be F2 rather than F3. The CI+ group (i.e., children with high receptive cued speech proficiency) produced the F2 distinction in exactly the same way as children with typical hearing, whereas children in the CI- group (i.e., with low receptive cued speech proficiency) did not show any F2 difference between /s/ and /ʃ/. Children in the CI- group therefore do not seem to produce a clear F2 distinction between the alveolar and postalveolar places of articulation for these fricatives. An additional between-group effect was observed: children in the CI+ and CI- groups produced higher F3 for /s/ than for /ʃ/. Given the lack of data on formant values at consonant offsets in children, these differences are difficult to interpret and call for articulatory-acoustic simulations using a model such as VLAM (Menard et al., 2007). In sum, the F2 contrast observed suggests that the children with cochlear implants and high cued speech proficiency were able to distinguish between fricative places of articulation as efficiently as children with typical hearing. Children with lower cued speech proficiency, on the other hand, did not produce the typical F2 contrast for the fricatives. This pattern was also observed for the center of gravity: for children in the CI- group, centers of gravity did not differ according to the fricative, whereas children in the CI+ and TH groups produced a higher center in /s/ than /ʃ/, exhibiting the expected place of articulation pattern. In addition, the difference between mean centers of gravity in /s/ and /ʃ/ was significantly lower in the CI- than in the CI+ and TH groups. These observations plead for the view that, for fricative consonants too, the higher the receptive cued speech proficiency, the more typical the acoustic differentiation. As predicted in our theoretical framework, enriched phonological representations provided by cued speech may lead to better specified articulatory gestures and better consonant production. It should be noted that the statistical power of the F2 and F3 feature analysis was relatively low, contrary to that of the center of gravity, which might prove a better acoustic correlate for fricative place of articulation in children. It is crucial to record more data to complete this sample and specify the relevant acoustic measurements.

Articulatory measurements revealed that the MCI values of all three groups were lower in /s/ than in /ʃ/, which is consistent with adult production. There was no contrast difference between groups. That is, the CI-, CI+ and TH groups similarly varied in tongue contours according to fricative consonants (see Appendix 6). The statistical power for this feature is quite low, more data are needed to confirm this effect and the relevance of this measurement for analyzing children's articulatory gestures for fricative consonants. As concerns the second articulatory measurement, the highest point of the tongue for /s/ was more anterior than that of /ʃ/ in the CI+ group, whereas the CI- and TH groups did not significantly distinguish between the two consonants on this dimension. Moreover, the contrast between the highest points of the tongue for the two fricatives was higher in the CI+ than in the TH group. These findings suggest that cued speech proficiency may allow children with cochlear implants to produce an even more accurate distinction between late-acquired fricatives than children with typical hearing. This is consistent with our theoretical framework, which posits that cued speech may enrich phonological representations and improve articulatory specification. However, no group effect was found for constriction place, and all groups produced a more anterior place of constriction in /s/ than in /ʃ/, with no contrast difference between groups. Nevertheless, the statistical power for the front-back index and for the constriction place is very low which does not allow us to draw any conclusions about the relevance of these measures or the ability of

children to distinguish between fricative phonemes on the basis of these articulatory contrasts. More data are needed to understand the articulatory strategies used by children to produce sibilant fricatives.

In brief, this exploratory study sheds light on a set of acoustic and articulatory measurements that can be performed in children using a non-invasive technique (i.e., lingual ultrasound). Moreover, the results of this study argue in favor of using articulatory measurements to further assess speech production in children. Indeed, some differences may appear between acoustic and articulatory measurements, which may be an indicator of differences in phonological specification. Our acoustic results revealed that CI-, CI+ and TH children all seemed to satisfactorily distinguish between alveolar and velar stops. This was confirmed by articulatory measures related to the highest point of the tongue, but the tongue curvature measure indicated that CI- children produced a weaker stop contrast than the other groups. Regarding fricative consonants, acoustic data revealed that CI- children had difficulties distinguishing between /s/ and /ʃ/ according to centers of gravity. Articulatory data in this group revealed that Modified Curvature Index was typically produced. Data on the front-back index of the highest point of the tongue and on constriction place did not prove statistically clear enough to characterize fricative articulation. The differences found between acoustic and articulatory measures indicate that children with lower cued speech proficiency may use specific articulatory strategies, which differ from peers with typical hearing or with a higher cued speech proficiency. They confirm that using acoustic measures alone, or a single articulatory measure, is not sufficient to fully characterize speech production in children (Barbier et al., 2020). In addition, our results highlight a tendency to distinguish more precisely the place of articulation of stop and fricative consonants in children with cochlear implants with a high cued speech proficiency, who reached acoustic and articulatory productions akin to those of their typically hearing peers.

Influence of the ultrasound probe on speech production

Although studying articulatory gestures by using ultrasound is not an invasive technique, placing the probe under the child's chin can disturb the production of a number of phonemes, in particular by slightly constraining jaw movements. A study by Villegas et al. (2015), found a small but not significant effect of the ultrasound probe on jaw movements, with over-articulation with the ultrasound probe. Pucher et al. (2020), for their part, have shown that some stabilization headsets may influence formant values in vowel production. To ensure the reliability of our results in the ultrasound modality, a first series of recordings without the probe was performed. The comparison of these two modalities (i.e., noUS vs US) showed an effect of the probe on some acoustic measurements. An effect of the ultrasound probe was observed on the F2 and F3 values of the consonant /k/ in children with cochlear implants and high cued speech proficiency (i.e., CI+ group). In fricative production, an effect of the ultrasound probe was observed on the F2 values of /s/ and /ʃ/ in TH, on the F3 values of /ʃ/ in CI- and CI+ and on the center of gravity of /s/ in CI-. A slight effect was also observed on the F2 values of /s/ in CI+. However, these differences between modalities did not influence the distinction between places of articulation: formant values can be higher or lower with the addition of the ultrasound probe but the difference between consonants is not altered.

These results show that the ultrasound probe may impact the production of stop and fricative consonants in children but this modification of the movements of the jaw

does not interfere with the distinction between places of articulation. Therefore, this modification does not invalidate our results concerning acoustic and articulatory measures during stop and fricative consonant production. However, it is important to emphasize this point and to keep this observation in mind when making acoustic and articulatory measurements by ultrasound.

Our results also have important clinical implications. Our data provide quantitative measures about how children with cochlear implants and children with typical hearing articulate stop and fricative consonants. Such data, especially in French, could help better understand the link between speech motor development and sensory deprivation, mediated or not by exposure to cued speech. Furthermore, in view of recent studies showing how ultrasound images used as a biofeedback technique can be used to improve speech production in clinical settings, as in Haldin et al. (2022) and Preston et al. (2020), it would be interesting to test the effects of ultrasound biofeedback in CI children who are exposed to cued speech. It is likely that since these children have gained refined abilities to decode the visual code, using a visual modality like ultrasound imaging to finely tune speech motor control might be very useful.

Limitations

Although the results of this exploratory study support the hypothesis that cued speech proficiency may improve the production of acoustic and articulatory correlates in children with cochlear implants and thus allow them to produce stops and fricatives in the same way as their peers with typical hearing, some limitations should be noted. First, the sample size of our study is small and the same analysis will need to be carried out with more participants. Particularly, the analysis of fricative consonants only includes two children in the CI- group, which does not allow us to make solid conclusions, but rather to highlight trends in their articulatory gestures. More participants would also allow us to increase the statistical power on several measures (i.e., F2 and F3 in fricatives and all articulatory features) and, therefore, to pinpoint more precisely the acoustic and articulatory correlates relevant to the study of consonant production in children.

Moreover, our study compares children with cochlear implants according to their cued speech proficiency. In order to better characterize the positive impact of cued speech on the production of stop and fricative consonants in children with cochlear implants, it will be necessary to supplement these data by recording children with cochlear implants who have never been exposed to cued speech. Another factor that should potentially influence speech production is duration of cued speech exposure. Many studies have shown that the longer the exposure, the higher the decoding skills (Clarke & Ling, 1976; Périer et al., 1990; Leybaert & Charlier, 1996). In our sample, only one participant in the CI+ group had been exposed for only 14 months to Canadian French Cued Speech. All the other participants had been exposed to Canadian French Cued Speech for, at least, 48 months. However, as argued by Machart et al. (2020, in prep), but also by Colin et al. (2015, 2017), a long exposure to cued speech does not seem to be sufficient to promote speech development in children with cochlear implants. Indeed, cued speech proficiency seems to play a more important role in speech production.

The age at implantation could also influence speech production, but our present sample only includes one child in the CI- group with an early implantation (i.e. before 24 months). Our observations therefore seem to confirm that cued speech proficiency can compensate for a late implantation, and allow children with cochlear implants to reach similar production to peers with typical hearing.

As mentioned in previous studies (Machart et al., 2020, in prep), socioeconomic status may also influence the development of cued speech proficiency and, therefore, the development of speech production in children with cochlear implants. It would be important to further examine the influence of this factor on speech production abilities. Since our groups were too small and heterogeneous with regard to these factors, it was not relevant to integrate them into our statistical models. Further studies, with more participants, should take these factors into account to more precisely describe the impact of Canadian Cued French exposure on consonant production in children with CIs.

CONCLUSION

The preliminary results of this exploratory study support the claim that cued speech proficiency might sustain the development of speech production in children with cochlear implants, by enriching their phonological representations and improving their articulatory gestures, particularly for plosive and fricative consonants. Our data suggest that higher cued speech proficiency compensates for the non-visibility of posteriorly articulated phonemes, and complements phonological representations, which seems to allow children with cochlear implants to have more richer phoneme specification, both in terms of acoustic and articulatory correlates, leading to more accurate tongue gestures. In this small cohort of children aged between four and eleven, participants with high cued speech proficiency displayed acoustic and articulatory contrasts related to fricatives and stops which were on par with those of their typically hearing peers.

Finally, this work highlights the importance of studying objective data and comparing acoustic and articulatory measurements to better characterize speech production. Further investigations with larger number of participants and a group of children with cochlear implants who have never been exposed to cued speech are needed to confirm our observations.

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DATA AVAILABILITY STATEMENT

Data are available upon reasonable request to the corresponding author.

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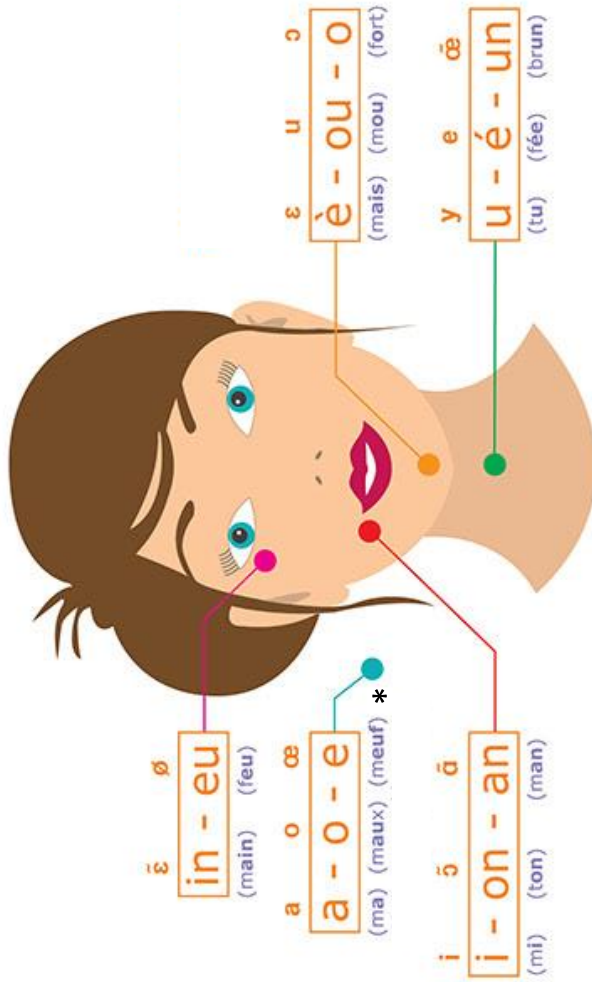
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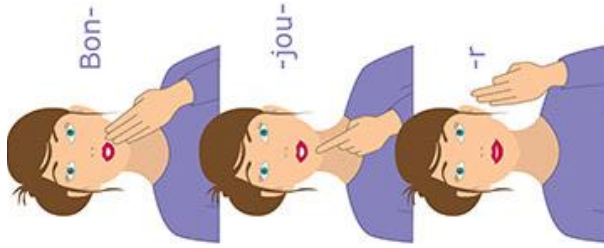
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Hand positions for vowels

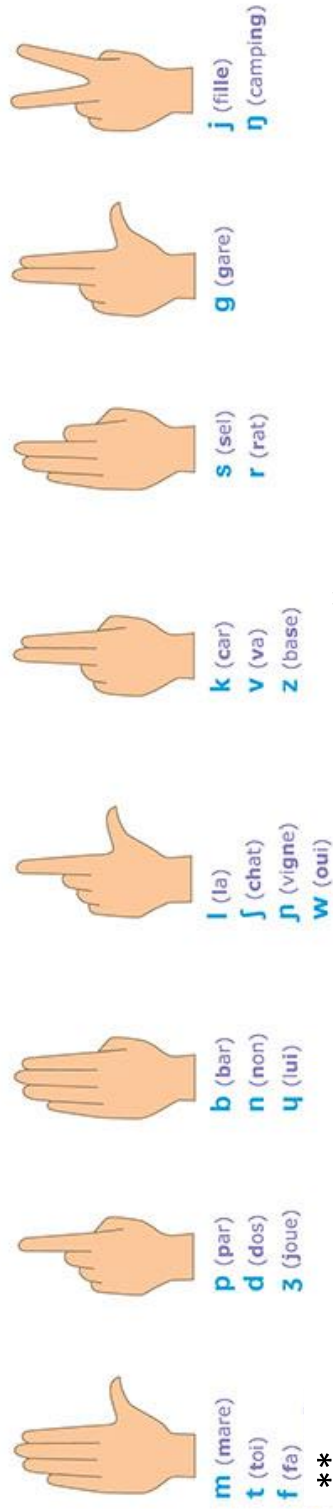


Cues for the French word *bonjour* /bɔ̃ʒuʁ/ (hello)



* This position is also used when a consonant is isolated or followed by a schwa

Handshapes for consonants



** This handshape is also used for a vowel not preceded by a consonant

Appendix 2: Canadian French Cued Speech reading scale.

Date :
Participant :
SLT :

Canadian French Cued Speech reading level



Low	Medium	Good	High
Few syllables are decoded at slow speed, in particular according to lip reading	Few familiar words are decoded at slow speed	Words and simple sentences are decoded at a slightly reduced speed of speech	Words and simple or complex sentences are decoded at speed of speech

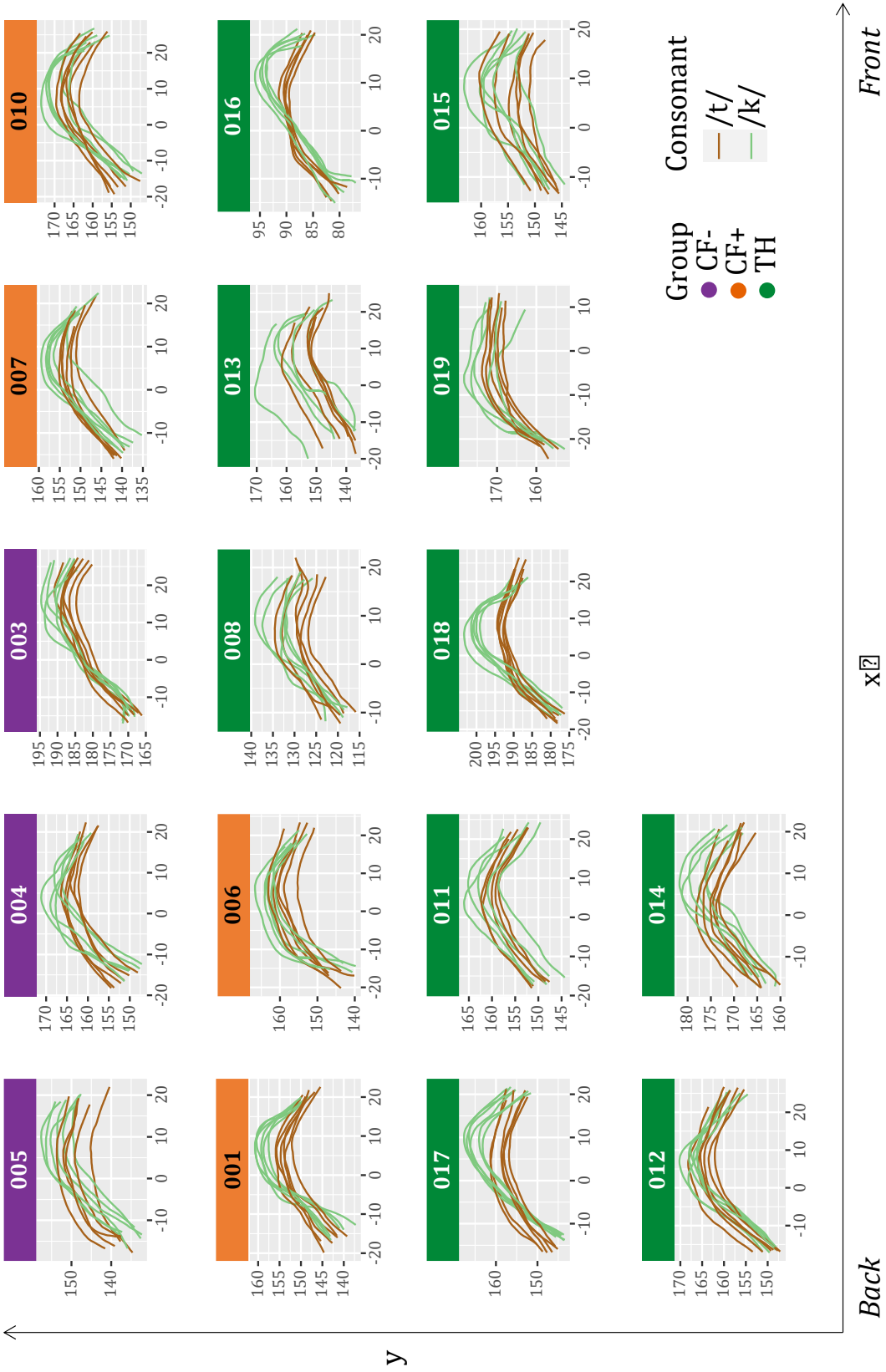
Appendix 3: Deviations from the OSF pre-registration

Pre-registration	Actual study
Groups	
<ul style="list-style-type: none"> • Control group with typical hearing • Control group with children with cochlear implants never exposed to Cued French • Experimental group with children with cochlear implants exposed to Cued French 	<ul style="list-style-type: none"> • Control group with typical hearing • Experimental group with children with cochlear implants exposed to Cued French <ul style="list-style-type: none"> ○ CI-: participants with low Cued French proficiency ○ CI+: participants with high Cued French proficiency
<p>Due to the pandemic, it was not possible to record data for a control group of children with cochlear implants who had never been exposed to Cued French. As a result, the group of deaf children with cochlear implants was divided into two subgroups, in order to observe the effect of Cued French proficiency rather than the effect of Cued French exposure (which was not possible without a group of children with cochlear implants without Cued French).</p>	
Material	
HOCUS (<i>Head-Optically_Corrected Ultrasound System</i>) (Whalen et al., 2005)	SonoSite 180 Plus ultrasound system (Turgeon et al., 2017)
Acoustic analysis	
<ul style="list-style-type: none"> • Stop consonants: F1 and F2 at vowel onset (i.e., consonant offset) and at mid-vowel • Fricative consonants: four spectral moments (i.e., center of gravity, standard deviation, skewness and kurtosis) 	<ul style="list-style-type: none"> • Stop consonants: F2 and F2 at vowel onset (i.e., consonant offset) • Fricative consonants: F2, F3 and first spectral moment (i.e., center of gravity)
<p>Since the aim of this study was to observe the distinction in place of articulation for plosive and fricative consonants, acoustic analysis was centered on acoustic parameters commonly used to describe place of articulation.</p>	
Articulatory analysis	
<ul style="list-style-type: none"> • Modified Curvature Index (MCI) as in Dawson et al., 2016 • Antero-posteriority index as in Ménard, Toupin, et al., 2013 which refers to the x-coordinate of the highest point of the tongue 	<ul style="list-style-type: none"> • Modified Curvature Index (MCI) as in Dawson et al., 2016 • Antero-posteriority index as in Ménard, Toupin, et al., 2013 which refers to the x-coordinate of the highest point of the tongue • Constriction place as in Ohkubo & Scobbie, 2019 which refers to the x-coordinate of the closest point of the tongue to the palate
<p>Since data was available an analysis of constriction place was added to be more precise regarding the articulatory distinction between places of articulation. Indeed, the closest point of the tongue to the palate does not correspond to the highest point of the tongue. Thus, the constriction place allows us to analyze the lingual gesture relative to the palate, while the antero-posteriority index indicates the position of the tongue in the mouth.</p>	

Appendix 4: Productions deemed perceptually acceptable for each consonant, by participants (classified by group and chronological age). Grey boxes indicate productions which are not part of the statistical analyses.

Speaker	Group	Production score (%)			
		/t/	/k/	/s/	/ʃ/
005	CI-	83	100	100	83
004	CI-	100	100	100	100
003	CI-	100	100	100	0
007	CI+	100	100	100	100
009	CI+	0	100	100	100
010	CI+	100	100	100	100
001	CI+	100	100	100	100
006	CI+	100	100	100	100
008	TH	100	100	100	100
013	TH	100	83	100	100
016	TH	100	100	100	100
017	TH	100	100	100	100
011	TH	100	100	100	100
018	TH	100	100	100	100
019	TH	83	100	100	100
015	TH	100	100	100	100
012	TH	100	100	100	100
014	TH	100	100	100	100

Appendix 5: Tongue contours for each stop consonant (/t/ in brown, and /k/ in light green) by group (CI- in purple, CI+ in orange, and TH in dark green). In each group, participants are ranked by chronological age.



Appendix 6: Tongue contours for each fricative consonant (/s/ in pink, and /ʃ/ in blue) by group (CI- in purple, CI+ in orange, and TH in dark green). In each group, participants are ranked by chronological age.

