A Comparison of Vowel Productions in Prelingually Deaf Children Using Cochlear Implants, Severe Hearing-Impaired Children Using Conventional Hearing Aids and Normal-Hearing Children

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Vowel production · Deafness, prelingual · Children · Cochlear implants

Abstract
Objective: The purpose of this study was to compare vowel productions by deaf cochlear implant (CI) children, hearing-impaired hearing aid (HA) children and normal-hearing (NH) children. Patients and Methods: 73 children [mean age: 9;14 years (years;months)] participated: 40 deaf CI children, 34 moderately to profoundly hearing-impaired HA children and 42 NH children. For the 3 corner vowels [a], [i] and [u], \(F_1\), \(F_2\) and the intrasubject SD were measured using the Praat software. Spectral separation between these vowel formants and vowel space were calculated. Results: The significant effects in the CI group all pertain to a higher intrasubject variability in formant values, whereas the significant effects in the HA group all pertain to lower formant values. Both hearing-impaired subgroups showed a tendency toward greater intervowel distances and vowel space. Conclusion: Several subtle deviations in the vowel production of deaf CI children and hearing-impaired HA children could be established, using a well-defined acoustic analysis. CI children as well as HA children in this study tended to overarticulate, which hypothetically can be explained by a lack of auditory feedback and an attempt to compensate it by proprioceptive feedback during articulatory maneuvers.

Introduction
Speech in prelingually deaf children is characterized by deficits in articulation of consonants and vowels [1]. Vowel production by hearing-impaired children contains certain types of articulatory errors such as diphthongation, substitutions and neutralization, and suprasegmental errors such as nasalization and hoarseness [1–5].

Cochlear implantation has become a standard procedure in the treatment of prelingually deaf children. Even though these implants primarily facilitate speech perception, they are also an important aid to the development of several aspects of speech production such as overall intelligibility [6], suprasegmental features [7] and the production of consonants [8] and vowels [9]. Serry and Blamey [9] found that the production of vowels, and especially of monophthongs, improved after implantation. Monophthongs were acquired earlier and more accurately than diphthongs and consonants, suggesting a relative ease of production of monophthongs compared to the other sound classes [9]. This difference between vowel and consonant production was confirmed by Van Lierde et al. [8], who found normal vowel production in prelingually deaf children with cochlear implants (CI), whereas consonant production showed several deviations such as distortions, substitutions and omissions. However, in the study by Tobey et al. [10], the accuracy of phoneme pro-
duction in CI children was even lower for vowels (61.6%) than for consonants (68%).

To describe the quality of vowel production, one can apply either a subjective descriptive analysis such as phonetic transcription, or an objective acoustic analysis of formant frequencies. The first two formants ($F_1$ and $F_2$) are considered to be the most important because, based on those two formants, a listener will be able to identify a specific vowel [11]. Determination of $F_1$ and $F_2$ frequencies of vowels offers the possibility to describe vowels in terms of high/low and front/back placement of the tongue in the oral cavity. The vowels [a], [i] and [u] represent the extreme articulatory positions of the tongue in English as well as in Dutch [12]. Representing the formant frequencies of these vowels in an $F_1$-$F_2$ diagram yields a so-called ‘vowel triangle’. This triangle is a graphic representation of the articulation space for vowel production with [a], [i] and [u] acting as ‘corner vowels’. In hearing-impaired patients, several abnormalities concerning formant frequencies and vowel space are described, such as centralization of the first two formants [13] and small articulation movements, which implies a reduction in articulation space and vowel triangle size [2]. Yet, children with CI experience show vowel features closer to normal values. Uchanski and Geers [14] compared the second formant frequencies of the American English anterior vowel [i] and posterior vowel [o] of CI children with those of normal-hearing (NH) children and concluded that nearly all CI children produced the vowels with $F_2$ values within normal limits (88 and 87% of the children, respectively, for [i] and [o]). Also the CI children in the study by Camposi et al. [15] showed $F_1$ [a] and $F_2$ [a] values comparable to those of NH children. Yet, in the study by Liker et al. [16], the mean $F_1$ [a] of the CI children was significantly lower in comparison with NH controls at 2 of the 3 test moments, indicating reduced movements of the jaw, resulting in a smaller vowel space. The CI children also showed fronted vowel space due to consistently higher $F_2$ frequencies in comparison with the NH controls. The $F_2$ frequencies were higher for the back vowels, indicating that the vowel space in the CI children is, on average, smaller in comparison with the controls. Liker et al. [16] explained the fronting of the vowel space by the tendency of therapists, family and the children themselves to move the articulation to where it is more visible. Hocevar-Boltezar et al. [17] found a decrease in $F_1$ of the Slovenian vowels [u] and [i] in prelingually deaf children 6 months after implantation. Those changes caused better phonological differentiation between both vowels and a postimplant vowel space expansion.

It seems that acoustic analysis can reveal more and different information on vowel production in hearing-impaired children than transcriptions can do. Acoustic analyses of vowel formants may reveal more subtle distinctions which are not crossing the phoneme boundaries. In the study by Horga and Liker [18], CI children approached the vowel space of NH children more than profoundly deaf hearing aid (HA) children. The main purpose of the present study was to compare the vowel production of prelingually deaf CI children with moderately to profoundly hearing-impaired HA children who had better hearing thresholds, and NH children. An acoustical analysis of the three corner vowels [a], [i] and [u] was made using the Praat software [19]. In a previous study by Baudonck et al. [20] concerning consonant production, deaf CI children were also compared with moderately to profoundly deaf HA children. In this study, the CI children performed better although the HA children had better thresholds. Based on those results concerning consonant production and the improved vowel production after implantation as described in other studies, the authors of the present study hypothesize that vowel production by deaf CI children approaches the vowel production by NH children at least as much as the production by moderately to profoundly hearing-impaired HA children does.

**Subjects and Methods**

The protocol was approved by the ethics committee of the University of Ghent (reference No.: 06017) and was in accordance with the ethical standard stipulated in the Helsinki Declaration for research involving human subjects.

**Subjects**

Seventy-four prelingually hearing-impaired children, all enrolled in Flemish oral/aural rehabilitation programs before the age of 3 years, were selected to participate in this study. They all suffered from nonsyndromal congenital hearing loss, and each child received its first HA before the age of 3 years. A minimal nonverbal intelligence score of 80 and use of the Dutch oral communication mode was required. Forty prelingually deaf children [mean age: 8;8 years (years;months)] received a multichannel CI at an average age of 2;8 years. Thirty-one of them were implanted with the Nucleus implant (Cochlear Corporation), 5 with the Di-gisonic implant (Neurelec) and 4 with the Clarion implant (Advanced Bionics). Thirty-four children (mean age: 9;6 years) were bilateral conventional HA users with a moderate-to-profound hearing loss. All children had at least 2 years of experience with their current device (HA or CI), which was fitted by experienced audiologists. During testing, all devices were adjusted to each child’s usual amplification and processing settings. The control group consisted of 42 NH children with a mean age of 9;3 years.
For the 3 subgroups, information concerning chronological age and, where appropriate, age at first HA fitting, the most recent better-ear unaided hearing threshold (pure tone audiometry, PTA), the most recent free-field aided hearing threshold, and age at implantation is provided in table 1.

A Mann-Whitney U test showed that mean chronological age, duration of initial hearing loss and mean nonverbal intelligence quotient of the CI and HA groups did not differ significantly (p > 0.05). Regarding the audiometric data, recent better-ear unaided thresholds were significantly better in both HA groups (p < 0.001) compared to the CI group, while the aided thresholds in the free field condition showed no marked difference between the HA and CI groups.

Recording Procedure
All recordings were made in a quiet room at the children’s school or in the University Hospital Ghent. Speech samples were elicited by means of a picture naming test [21] in which children are asked to name black-and-white drawings of common objects and actions in order to elicit instances of all Dutch single speech sounds in all permissible syllable positions. Those speech samples were recorded directly on a portable computer (Toshiba M70 with Harman Kardon sound card), under standard conditions using a condenser stereo microphone (Sony ECM-MS907). For the recording, the examiners used the Praat software [19]. The Euclidian distance between the corner vowels along the axes of an F1–F2 scatter plot as well as the surface area of the vowel triangle were calculated. To guarantee a standardized protocol for all calculations, a Praat script (by P.C.) was systematically applied. Those calculations were completed accurately by the first author (N.B.) individually, consistently following the above-described procedure. As a control procedure, a remeasurement of formant values was done by the last author (P.C.) for 8 randomly selected children. As a control procedure, a remeasurement of formant values was done by the last author (P.C.) for 8 randomly selected children (10%).

Acoustic Analyses
For the 3 corner vowels [a], [i] and [u] of each child, 10 midvowel fragments with stable formant patterns were selected from the same 10 monosyllabic words or stressed syllables of bisyllabic words. The midvowel segments were selected using visual inspection of the oscillogram and the spectrogram. Fragments showing the most stable formant patterns were identified, extracted without formant transitions, and regrouped into one comprehensive sound fragment (mean total duration: 0.81 s), which was then submitted to the formant detection algorithm. The Burg algorithm for formant detection was used with a 0.025-second gaussian analysis window (effective duration) and +6 dB preemphasis from 50 Hz onwards. The formant search range was limited to 8,000 Hz to adapt the algorithm to the dimensions of children’s vocal tracts. For each vowel fragment of each child, a specific amount of linear predictive coding coefficients was determined, based on visual inspection of the spectrogram and spectrum, and on intrasubject variability in formant values (the number of coefficients was chosen in such a manner that the formant SD of all analysis frames were as low as possible). For further verification, the obtained formant values were compared with the formant values from English-speaking children of comparable ages, as described by Vorderman and Kent [22] as well as with formant values from Dutch men as described by Pols [23]. In case of doubt, because of a salient contrast with the values from the latter references (taking into account language and age differences) or because of high intrasubject variability, another set of 10 midvowel segments was selected and the whole procedure repeated in order to find a plausible formant value.

The 50th percentile value of the first (F1) and second formant frequency (F2) as well as the intrasubject SD were measured for each vowel of each child using the Praat software [19]. The Euclidian distance between the corner vowels along the axes of an F1–F2 scatter plot as well as the surface area of the vowel triangle were calculated. To guarantee a standardized protocol for all calculations, a Praat script (by P.C.) was systematically applied. Those calculations were completed accurately by the first author (N.B.) individually, consistently following the above-described procedure. As a control procedure, a remeasurement of formant values was done by the last author (P.C.) for 8 randomly selected children (10%). For F1, the mean difference between the values by both examiners was 20 Hz (range: 3–61 Hz). For F2, the mean difference between the values by both examiners was 58 Hz (range: 2–101 Hz).

Statistical Analyses
SPSS for Windows (version 15.0) was used for the statistical analysis. The results of the CI children were compared with the results of the HA and NH children. The Kolmogorov-Smirnov test (α = 0.01) and the Shapiro-Wilk test were performed to study the distribution of the variables. The variables ‘F2 [a], [i] and [u]’ and ‘intrasubject SD F2’ deviated from a normal distribution (p < 0.05 on either the Kolmogorov-Smirnov or the Shapiro-Wilk test), whereas the remaining variables were normally distributed. For the comparisons between the 3 subgroups, a one-way ANOVA in combination with a post hoc Scheffé test was applied in case of normal distribution. In case of a deviation from a normal distribution, Kruskal-Wallis tests were executed to document possible differences between the 3 subgroups. When the obtained p was smaller than 0.05, pairwise comparisons were executed using a Mann-Whitney procedure. The significance level was set at α = 0.05 in all tests.

Table 1. Demographic information on participants in this study

<table>
<thead>
<tr>
<th>Number</th>
<th>Chronological age, years</th>
<th>Age at deafness, months</th>
<th>Age at first HA fitting, months</th>
<th>Unaided threshold PTA dB HL</th>
<th>Aided threshold PTA dB HL</th>
<th>Age at implantation, months</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH children</td>
<td>42</td>
<td>9;3 (4;3–15;3)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>HA children</td>
<td>34</td>
<td>9;5 (4;1–14;2)</td>
<td>0 (0–0)</td>
<td>13 (2–36)</td>
<td>80 (58–105)</td>
<td>34 (17–50)</td>
</tr>
<tr>
<td>CI children</td>
<td>40</td>
<td>8;8 (4;2–15;5)</td>
<td>0 (0–10)</td>
<td>11 (1–36)</td>
<td>109 (73–120)</td>
<td>33 (11–50)</td>
</tr>
</tbody>
</table>

Values are means with ranges in parentheses.
Results

Table 2 represents the mean formant frequencies, the mean intrasubject SD of the formant frequencies, the mean intervowel distances, the mean vowel space and the p values of the comparisons between the 3 subgroups. Concerning vowel [a], the CI children did not show significantly different formant values compared to the NH children, while there was a significantly lower F2 in the HA children compared to the NH children. The CI children, on the other hand, showed a slightly higher but significant intrasubject variability for both formants compared to the NH children, as shown by the higher SD. No significant differences were detected between the CI and the HA groups for vowel [a] parameters. For the vowel [i], a scarcely significant lower F2 value was found for the HA group compared to the CI group. No differences could be found between the formants of the vowel [i] of CI and NH children. Concerning the vowel [u], there were no statistically significant differences between both hearing-impaired groups. The HA children showed a significantly lower F1 and F2 [u] than the NH children. In the CI group, a higher intrasubject variability in the F1 [u] was found. As seen in table 2, the hearing-impaired children systematically showed the highest values for all intervowel distances /i-u/, /a-i/ and /u-a/ as well as for the vowel space, whereas the NH children systematically had the lowest values. In both hearing-impaired groups, a tendency toward an increased vowel space compared to NH children was found. The /a-u/ difference between the NH children and both hearing-impaired subgroups, and the /a-i/ difference between the CI and NH children were statistically significant, while no significant differences between the HA and CI children were found. The vowel triangles of the 3 subgroups are represented in figure 1.

Discussion

The main purpose of the present study was to compare prelingually deaf CI children with moderately to profoundly hearing-impaired HA children and NH children with regard to vowel production. An acoustical analysis of the three corner vowels [a], [i] and [u] was made using the Praat software. The hypothesis was that vowel production in CI children would be closer to normal than in HA children. Generally speaking, both hearing-impaired groups showed several significant differences when compared to the NH group. The significant effects in the CI group all pertain to a higher intrasubject variability in
formant values, whereas the significant effects in the HA group all pertain to lower formant values.

The first remarkable formant differences were related to the vowel [a]. Compared to NH children, the F2 [a] was lower in the HA children. The CI children showed a higher intrasubject variability for both formants of the vowel [a], as measured by SD, which hypothetically indicates some articulatory vacillation in the production of [a] even after implantation. However, based on the fact that the F2 values of the CI children in the present study resemble normal values more than those of the HA children do, one can conclude that cochlear implantation probably has a subtly positive impact on the place of articulation of [a]. In the study by Campisi et al. [15], the values of CI children were compared with age-matched control data [24]. In agreement with the present study, no differences between CI and NH children were found for formant frequencies of [a]. Concerning the formants of the front vowel [i] and dorsal vowel [u], the CI children in this study did not show significant differences from their NH peers. This is in agreement with Uchanski and Geers [14], who found that nearly all of 181 CI patients produced the front vowel [i] and back vowel [o] with F2 values within normal limits. On the other hand, for the HA children in the present study, both formants of the vowel [u] were decreased in comparison with normal values. Hypothetically, the decreased F1 [u] can be explained by the fact that HA children usually show more residual hearing at low frequencies. On that account, it seems that they seek to produce the first formant, which is also the most intense among formants, as low as possible in an attempt to enhance auditory feedback. In the CI children, the F1 [u] was also lower compared to the NH children although this difference was not significant. As was the case for [a], CI children showed an increased intrasubject variability in F1 [u], as measured by SD.

The decreased F2 [u] in the HA children can indicate a tendency toward a more dorsal articulation of the vowel [u]. The production of the [u] turns out to be a potentially difficult speech parameter for hearing-impaired children, especially for children using HA. Concerning the front vowel [i], the F2 was slightly decreased in the HA children in comparison with NH and CI children. This trend was also seen for the vowels [a] and [u]. It seems to support Boone’s theory that hearing-impaired children tend to keep their tongues too far back in their mouths [25]. Nevertheless, one should pay attention when considering only the means of values for F2 in the three subgroups in the present study. Although significantly lower mean F2 results were found in the HA group, a huge overlap between the three subgroups cannot be denied when looking at the range and SD. This means that although, on average, the HA group shows decreased mean F2 values in comparison with the normal hearing controls, many hearing-impaired children still perform within normal ranges.

In the CI children, no significant differences were found for F2 frequencies, thus backing or fronting of the vowel space was not observed. Liker et al. [16], however, found fronted vowel space in CI children due to consistently higher F2 frequencies. In their study, F2 frequencies of back vowels were clearly increased, yielding vowel space values for CI children that were, on average, smaller than in NH controls. This concomitant reduction in vowel space is also in contrast with the results of the present study. The increase in F1 [a] values, although not significant, caused more salient /i-a/ and /u-a/ contrasts in both hearing-impaired groups of the present study, in comparison with the NH subjects. As a consequence, the area of the vowel triangle tends to be larger in the CI as well as in the HA groups. In some respects, these results are rather surprising and contradictory to previous research in which a reduction in vowel triangle size was found in hearing-impaired patients [13].
This contradiction with previous research partly may have been brought about by language differences, but hypothetically, the phenomenon of an increased vowel space could also be explained by a tendency of therapists and family to exaggerate their articulation movements in order to facilitate speech reading. Probably, hearing-impaired children imitate this trend and even use the exaggerated movements themselves in order to enhance proprioceptive feedback. Thus, these unexpected results can be explained by the same simple rationale, i.e. excessive articulation movements which hearing-impaired children probably use, imitating their models in order to improve visual and proprioceptive feedback. Indeed, since neonatal hearing screening is well organized in Flanders, rehabilitation typically starts at a very early age. Hearing-impaired children receive speech therapy from early childhood on and are trained intensively to compensate speech production deficits. Liker et al. [16] found a smaller vowel space for CI children in comparison with NH controls. It is worth mentioning that the children in the study by Huber et al. [24] started rehabilitation at a later age (mean: 4.5 years; range: 1.10–7.8 years) than the participants in the present study (before the age of 3 years). Hypothetically, early and intensive articulation training in order to compensate speech production deficits could have led to overarticulation in the hearing-impaired children of this study. Yet, overarticulation of vowels has no harmful effect on speech intelligibility.

Besides processing spoken utterances in a purely linguistic way by extracting canonical categories such as phoneme and word units, listeners simultaneously encode nonlinguistic perceptual characteristics [26]. Those are audible deviations from the pronunciation standard that do not necessarily interfere with a correct identification of speech sound categories or overall intelligibility. For instance, the degree of fine-grained variation in synthesized speech is linked to both intelligibility and naturalness ratings [27]. The formant values and dispersions in the speech of the CI and HA children of the present study are possible candidates too. Thus, besides being correlated with intelligibility, the observed subtle acoustic formant distinctions, some of which can remain undetected by the naked ear, may perhaps signal deficits in ‘naturalness’ of a child’s speech. When it comes to vowel production in early-rehabilitated hearing-impaired children, further research should pay more attention to speech ‘naturalness’ rather than to intelligibility.

The authors are aware that the variability in the several subgroups is great, and that the number of possibly influencing factors is considerable. Multiple variables can affect the speech performance of children. The age at onset of deafness, age at first hearing device, age at implantation, type of device and degree of hearing loss are known variables in this study. In contrast, variables such as the quality of an educational program, children’s and parents’ self-efficacy beliefs [28], children’s motivation [29] as well as other family, school and community factors are unknown and are all factors which can influence speech production. Since there was a considerable range of age at implantation relative to age at time of testing in this study, there was also a wide range of CI experience. It would be very interesting to investigate the influence of CI experience on the evolution of vowel formants. Yet, in the present study, the subgroups were too small to compare reliably when children were regrouped on the basis of a clear difference in months of CI experience. A substantial number of patients are needed to avoid variability and find significant differences. However, such a number of patients are not available in Flanders. It should also be noted that the CI group in Flanders – and, as a consequence, the participants in this study – consists of unilaterally as well as bilaterally implanted children. To what extent bilateral implantation has an impact on the speech production skills of prelingually deaf children is a subject of further research.

In conclusion, we can state that, in this study, several subtle deviations in the vowel production of prelingually deaf children could be established using an objective acoustic analysis. Children using HA showed a tendency toward a more dorsal articulation of the vowels, which was not seen in the CI children. Both hearing-impaired groups showed a tendency toward overcompensation while articulating, possibly following the example of parents and therapists and, perhaps, as a side effect of early and intensive rehabilitation. This conclusion can be explained by a lack of auditory feedback and the search for more proprioceptive feedback during articulatory maneuvers.

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