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Intrinsic vowel fundamental frequency in children with and without hearing impairment

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Abstract

Introduction

It is well-established that high vowels tend to have a higher F0 than low vowels, a phenomenon known as Intrinsic Vowel F0 (IF0). However, the underlying cause of IF0 remains debated. Previous research suggests that IF0 is entirely of physiological origin, while other research indicates that it is acquired to enhance perceptual contrasts between vowels.

Methods

This study explored the impact of hearing loss on IF0 in six-year-old children, both with and without hearing impairment. The Belgian Dutch vowels produced by the children in both groups during a (non-)word repetition task were acoustically analysed for F0.

Results

The main result was that all children presented IF0. Although IF0 was not significantly different between children with and without hearing impairment, there was a trend towards a smaller IF0 in the hearing-impaired group.

Conclusion

In conclusion, while the results of this study support the physiological hypothesis, they also suggest a potential role for perceptual factors in shaping IF0. The results were interpreted in relation to the combined potential effects of speech organ physiology and perception on IF0.

Introduction

In adult speech, the high vowels /i/ and /u/ typically exhibit a higher F0 than low vowels, such as /a/ (among others: [1, 2, 3, 4, 5, 6]). This phenomenon is commonly referred to as intrinsic vowel F0 (henceforth: IF0) or intrinsic vowel pitch.

Since its earliest description by Crandall [7], cross-linguistic research on IF0 in adult speech has suggested that IF0 is a universal feature of spoken languages with only few exceptions. In their review, Whalen and Levitt [3] analysed the F0 data of 31 languages representing 11 language families, ranging from Dutch (West Germanic) to Japanese (Japanese), Paraok (Mon-Khmer) and Navaho (Athabaskan). These languages represented a wide range of prosodic systems such as stress, tone and pitch accent languages. It was concluded that the F0 difference between the high vowels [i] and [u] and the low vowel [a] was statistically significant in all these languages. Subsequent research on additional languages has largely confirmed these findings (e.g., [8] but see [9]).

Despite the well-established nature of IF0, its precise cause remains a matter of debate. IF0 has been attributed to various factors: (i) the physiology of vowel production, (ii) perceptual enhancement and (iii) a mix between (i) and (ii). The physiological hypothesis posits that IF0 results from the biomechanical link between the articulatory and phonatory systems in speech production. The movements of the tongue necessary for the articulation of high vowels exert force on the larynx, affecting vocal fold tension. Consequently, different degrees of tension triggered by the high and low vowels cause F0 differences between these vowel categories. The exact nature of this biomechanical link remains a matter of debate [1, 10, 11, 12, 13, 14, 15, 16, 17, 18].

In contrast, the perceptual enhancement hypothesis argues that IF0 results from speakers' deliberate efforts to improve perceptual distinctions between vowels. According to this hypothesis, F0 can be actively controlled by speakers to enhance the perceptual contrast between high and low vowels, suggesting that IF0 has perceptual significance [19, 20, 21]. This account is based on research by Traunmüller [2] and Syrdal and Gopal [22], who showed that listeners do not judge vowel height solely based on the frequency of the first formant (F1), but rather on the auditory distance between F1 and F0: the smaller this distance, the higher the perceived vowel on the vowel chart. Diehl [20, p. 126] suggests that speakers actively raise F0 in the production of high vowels (reducing the distance between F1 and F0) and lower F0 for low vowels (increasing the F1-F0 distance) in order to render the perceptual distinctiveness between the high and low vowels more salient. In this perspective, IF0 is considered as a feature which is actively used by speakers to enhance phonological vowel contrasts, especially in languages with a large vowel inventory. An argument in favour of the perceptual enhancement hypothesis is that IF0 has been observed in the oesophageal speech of laryngectomized speakers [23, 24]. In these speakers, the natural biomechanical link between the system of articulation and the larynx had been surgically removed, demonstrating at the very least, that speakers are aware of the functional relevance of IF0.

A third possible explanation holds that both the biomechanical link and perceptual enhancement play a role in IF0. This mixed hypothesis assumes that the physiological hypothesis and the perceptual enhancement account are in fact not mutually exclusive [4, 15]. It acknowledges the role of a biomechanical link between articulation and phonation, but hypothesises that the net effect of articulation on phonation is only a baseline effect which can be actively modulated by speakers as a function of perceptual needs. For instance, speakers in some languages have learnt to increase IF0 in order to enhance the perceptual distinctions between vowels. Research by Van Hoof and Verhoeven [4] supports this, showing that Arabic (3 vowels) has an IF0 of 7 Hz, while Dutch (12 vowels) has an IF0 of 21 Hz, suggesting that Dutch's larger vowel inventory necessitates greater perceptual enhancement.

The explanations of IF0 presented above have mainly been supported by research on adult speech and only very few studies have examined IF0 in children. Crucial insights into the mechanisms underlying IF0 can, nonetheless, be derived from early language acquisition and children’s hearing status.

In terms of early language acquisition, a study by Whalen et al. [25] found that babies as young as 6 months exhibit IF0 in both French and English. The fact that the children in this study showed IF0 without any evidence of a developmental effect or differences between the languages was interpreted as support for the idea that IF0 is an automatic consequence of vowel production. Conversely, Bauer [26] who analysed vocalic productions of 3 children between 10 and 13 months old did not find a correlation between F0 and vowel height, suggesting that IF0 may not be purely biomechanical but must be acquired. It should be noted, however, that both studies relied on relatively small sample sizes and differed significantly in methodology.

In terms of the effect of hearing status on IF0 in children, Bush [27] investigated F0 in the vowel productions of 33 children: 20 children with profound hearing loss (83+ dB HL) and 13 children with normal hearing. The hearing-impaired participants were aged between 9 and 17 years, while the typically hearing participants were aged between 10 and 16 years. The analysis of F0 in the high and low vowels revealed that the F0 in the high vowels was higher than in the low vowels, and this was the case in all children irrespective of their hearing status. This finding indicates that all children in this study exhibited IF0, which is consistent with the findings for adult speech.

Interestingly, Bush [27, 102] found a larger IF0 in the hearing-impaired group than in the children with normal hearing: IF0 hearing-impaired = 42.72 Hz (2.82 semi-tones), IF0 typically-hearing = 8.96 Hz (0.74 semi-tones). Although Bush [27] argues that the qualitative similarity between the IF0 effect in both groups is evidence for the articulatory nature of the IF0 effect, the larger size of IF0 observed in hearing-impaired children seems to suggest that the quality of auditory feedback may be relevant. These results suggest that IF0 may be dependent on children's hearing status, which would go against the physiological hypothesis. In fact, the physiological hypothesis does not predict any differences in the size of IF0 between normally-hearing and hearing-impaired children. That is, since both groups of children share the same biomechanical linkage between the systems of articulation and phonation, no significant differences in any direction are expected. Therefore, Bush's [27] seem to be consistent with the perceptual enhancement hypothesis, which emphasises the role of perception in IF0.

Although the results in Bush [27] are thought-provoking, the study had several limitations that may have had a bearing on the findings. Particularly important in this context is the wide age range of the children participating in the study: ages ranged from 9.6 years to 17.6 years with a mean age of 13.1. In addition, the males were on average younger than the females, 10.86 and 14.63 years respectively. Although there were some indications in the study that the acoustic data were normalized, the anatomical differences between all the participants are likely to be significant in this study.

The present study aimed to reassess the effect of hearing impairment on IF0 in children by studying IF0 in a homogenous group of age-matched children with and without hearing impairment.

The first research aim (**RQ1**) was to find out whether all children exhibit IF0, regardless of hearing impairment. In other words, it was investigated whether vowel height influenced F0 in the entire group of age-matched children. If all children exhibit IF0, this would support the physiological explanation of IF0, while not excluding the perceptual enhancement and mixed hypotheses.

The second aim (**RQ2**) was to investigate whether there are any IF0 differences between hearing-impaired children and their normally hearing peers. A significantly different effect of hearing status on the F0 of high versus low vowels would suggest that perceptual ability plays an important role in IF0, aligning more closely with the perceptual enhancement and mixed hypotheses.

The third aim of the present study (**RQ3**) was to examine whether device type in children with hearing impairment had an effect on IF0 by studying the F0 of high and low vowels in children with a conventional hearing aid (henceforth: HA) vs. children with a cochlear implant. The quality of input from a HA is more fine-grained than that from a CI (e.g., [28, 29, 30, 31]). Therefore, differences are expected between children with HA and children with CI if the enhancement or the mixed hypothesis holds. Children with poorer input might not reproduce IF0 as effectively as those with better access to fine-grained and functionally relevant F0 variations, with smaller IF0 effects expected in children with CIs due to the inferior quality of input.

Thus, the overall aim of the present study was to better understand the underlying mechanisms which cause IF0. In particular, the role of perception was studied by means of an analysis of vowel production in children with different degrees of hearing: children with normal hearing and children with a hearing impairment assisted by an acoustic hearing aid or a cochlear implant.

Methods

To address the research questions, the vowel productions of two groups of children were analysed acoustically for F0: one group consisted of children with typical hearing (NH) while the other group was composed of children with hearing impairment (HI). The latter group included both children with a conventional acoustic hearing aid (HA) and children with a cochlear implant (CI). The research procedure is summarized in Figure 1. This section systematically describes the consecutive steps in the methodology.

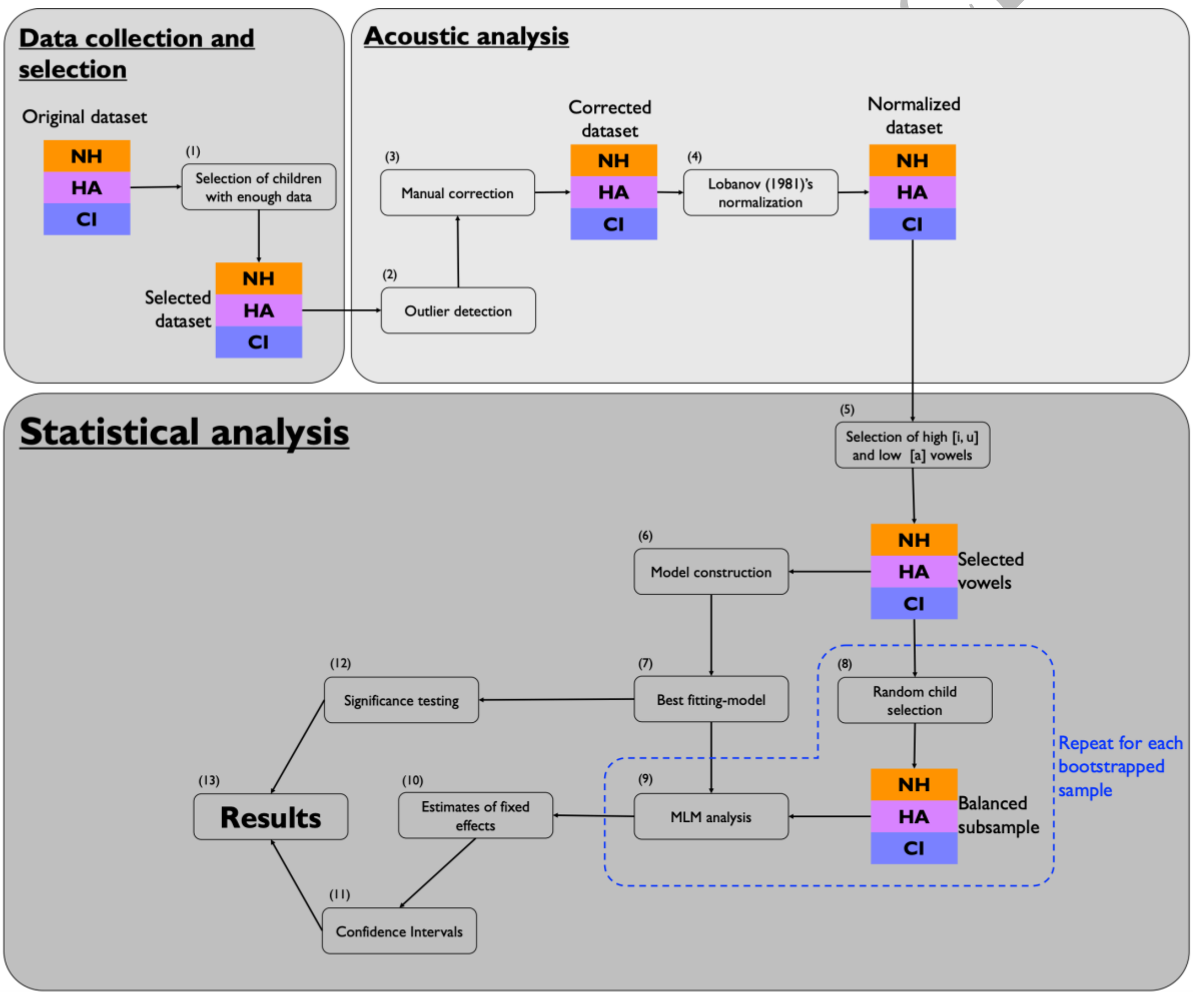

Fig. 1. Block diagram of the analysis procedure.

Participants

The participants were 105 Belgian Dutch-speaking children born from native speakers of Belgian Standard Dutch [32]. One group of 90 children had typical hearing according to informal reports from their parents and teachers. The median chronological age of these children was 6 years, with a minimum of 5 and a maximum of 7 years. They all attended their first year of primary school and had always lived in their geographical birth region up to the point of data collection.

In addition to children with typical hearing, the study also included 15 hearing-impaired children who differed in terms of the hearing support they received: 8 children had been fitted with a cochlear implant (CI) and 7 children used a conventional hearing aid (HA). The value of this dataset stems from the fact that all the hearing-impaired children attended mainstream schools. This setting allowed to recruit typically developing children from the same classes as the hearing-impaired children, thereby maximizing the match between the two groups. In this way, the normally hearing children were matched with the hearing-impaired children with a cochlear implant. The hearing characteristics of the children with hearing impairment are summarized in Tables 1 and 2:

Table 1: Hearing characteristics of the CI children.

	Mean	*Standard Deviation*
Chronological age (in months)	72.875	4.643
Unaided HL (in db HL)	112.125	9.478
Age at HA (in months)	3.25	1.753
HL with HA (in db HL)	89.75	28.729
Age at CI (in months)	11.375	5.012
Age at CI fitting (in months)	12.625	5.208
HL with CI (in db HL)	28.75	6.296
Device experience (in months)	60.25	5.825

Note. CI: cochlear implant; HA: hearing aid; HL: hearing loss. Gender: 5 females-3 males.

Table 2: Hearing characteristics of the HA children.

	Mean	*Standard Deviation*
Chronological age (in months)	73	1.732
Unaided HL (in db HL)	67.286	12.244

Age at HA (in months)	13.857	10.668
HL with HA (in db HL)	34.714	6.102
Device experience (in months)	59.143	10.367

Note. HA: hearing aid; HL: hearing loss. Gender: 3 females-4 males.

Data collection and selection

The vowel data used for this study were described in detail in Verhoeven, Hide, De Maeyer, Gillis, and Gillis [33] who studied the surface area of the vowel space, the formants and acoustic differentiation between the Dutch vowels. This speech corpus consisted of recordings of 36 monosyllabic (non-)words, specifically designed to include one of the 12 monophthongs of Belgian Standard Dutch, i.e. [i, ʏ, ɪ, ɛ, ɑ, ɔ, u, yː, eː, øː, aː, oː]. Each vowel occurred in three consonantal contexts: (i) [p_t], (ii) [l_t], and (iii) [t_r]. These contexts had been chosen to facilitate accurate and consistent segmentation of the vowels for acoustic analysis. The overall structure of the (non-)words was compatible with the requirements of the Dutch phonological system [34].

The (non-)words were initially read aloud and recorded by a trained female phonetician and native speaker of Standard Belgian Dutch. These pre-recorded stimuli were then played to the participating children, who were asked to repeat them. The stimuli were played to the children one by one via loudspeakers so that no visual lip-reading information was available to the participants. Each of the 36 stimuli was presented three times to the children, but for some children only one repetition could be obtained (see [35]). Children were required to repeat the phonetician's examples and their speech was recorded by means of a TASCAM DAT recorder and a headmounted MicroMic II in a quiet room. The audio files were formatted to WAV files using a TASCAM US 428 Digital Control Space. The recording sessions with the children yielded a total of 7,985 speech samples.

In the first instance, the children's speech samples were perceptually assessed by 6 expert listeners, who were asked to judge whether the children's vowel productions were accurate imitations of the target vowels. The perceptual assessment consisted of a multiple forced choice task that had been implemented in PRAAT [36]. The experts were informed that the children had different regional backgrounds and that they had a different hearing status (CI, HA or NH). They were asked to focus specifically on vowel quality. They were required to label children's vowel realisations as "correct", "incorrect", or "impossible to judge". In total, 7,261 vowel sounds (91%) were judged as accurate imitations of the target sounds. The correct imitation rates were 97% for the NH group, 84% for the CI group, and 77% for the HA group. Vowel errors were eliminated from the analyses, as these might not reflect the children's ability to produce a specific target but rather their difficulty in accurately perceiving and reproducing the auditory target.

In order to normalize the acoustic measurements, it was necessary to have at least one production of each vowel category and, as the analysis focused specifically on the corner vowels /i, a, u/, only the children who produced at least 2 repetitions of the corner vowels and at least one repetition of all the vowels in any context were included in this study (step (1) in Figure 1). As a result, a total of 57 children were included for further analysis: 47 NH children (22 boys and 25 girls), 5 HA children (4 boys and 1 girl) and 5 CI children (5 girls). In the end, the dataset consisted of a total of 5,557 vowel productions of which 1,463 were instances of the corner vowels /i, u, a/.

Acoustic analysis

Relying solely on F0 to compare the IF0 of two different groups, as has been the case in most traditional studies on IF0, could lead to misleading conclusions. If the physiological hypothesis holds, groups of children that distinguish high and low vowels with a greater difference in the degree of opening compared to other groups of children would, by definition, exhibit larger IF0s, and vice versa. Therefore, it is essential to control for spectral differences in terms of F1, which is traditionally used as an estimate of the degree of opening. Without such control, potential differences in F0 as a function of phonological vowel height cannot be solely attributed to variations in perceptual enhancement, but also to differences in articulation, affecting the tension of the vocal folds to varying extents. To address this issue, IF0 was calculated in two ways: first, as the difference in F0 between high and low vowels for comparison with other studies; and second, as the difference between high and low vowels in terms of the distance between F1 and F0. This difference was expected to be smaller for high vowels and larger for low vowels. In other words, the larger the contrast between high and low vowels in terms of the F1-F0 distance, the larger the IF0.

All vowels had been segmented and annotated by hand based on visual information in a broadband spectrogram produced in PRAAT [36]. Vowel F0 was computed using the Parselmouth API [37] of PRAAT via its standard auto-correlation algorithm. For each vowel, the mean F0 measurement was taken from the middle-third portion of the vowel in order to minimize the influence of the adjacent consonants on F0 [38]. The analysis parameters were as follows: maximum number of candidates = 15, silence threshold = 0.03, voicing threshold = 0.45, octave = 0.01, octave-jump cost = 0.35, and the voiced/unvoiced cost = 0.14. In order to minimize the risk of octave jumps, the pitch floor and ceiling were set at 175 Hz and 425 Hz respectively after visual inspection of the pitch contours with PRAAT's standard parameter settings. Additionally, PRAAT's "Kill octave jumps" function was activated. The F0 tracking algorithm was not able to measure F0 in 8 vowels and these were excluded from further analysis.

To investigate the effects of degree of opening, F1 was also measured as the average frequency in the middle third portion of each vowel using the following analysis settings: maximum number of formants = 5, maximum formant = 5500 Hz, window length = 0.025 and pre-emphasis = 50. To reduce potential tracking artifacts, the outlier detection technique described in Garellek and Esposito [39] was applied (step (2) in Figure 1). F0 and F1 measurements that were below or above 2.5 from the mean value for F0 or F1 of each individual child were corrected manually (step (3) in Figure 1).

The F0 measurements were carried out in Hz, but a z-score normalization of F0 [40] was used to reduce the potential effects of anatomical differences between children (step (4) in

Figure 1). The exact formula applied in the present study is provided in Equation 1 [41, 42, 43]:

$$(1)\ F0_{kt}^{Lobanov} = \frac{F0_{kti}^{Hz} - \mu_{kt}}{\sigma_{kt}}$$

where $F0_{kt}^{Lobanov}$ is the normalized F0 of token *i*, of vowel type *t*, produced by speaker *k*, meaning that the normalization factors (μ_{kt} and σ_{kt}) were computed based on the averages per speaker and per vowel type.

It should be emphasized that the measurements of F0 and F1 were normalized within each child, not for the three groups as a whole. Although this procedure irons out the effects of anatomical differences between speakers, it has been shown to preserve acoustic differences of phonemic and sociolinguistic origin [44]. Therefore, it can be assumed that differences related to hearing status are also preserved.

Statistical analysis

Given the intrinsically hierarchical nature of these data, multi-level modelling was used as the statistical technique. The data consisted of several items produced by different children grouped according to their hearing status. Multi-level modelling enables the analysis to cope with the hierarchical nature of the data and addresses violations of the assumption of compound symmetry and sphericity [45]. Models were built incrementally, adding random and fixed effects step by step to derive the best-fitting model for each research question. Each time, a likelihood ratio test was carried out to establish whether the inclusion of an effect significantly improved the fit between the predicted and observed values. The significance level for a model to be preferred over another one was set at $p < .05$. In the case of an equally good fit, the most parsimonious model was retained (steps (7) in Figure 1). This procedure was based on [46] and [47]. The statistical analyses were carried out in R [48] with the R package *lme4* [46]. The *lmerTest* package [49] was used to obtain p-values (step (12) in

Figure 1). The data points retained for the analysis were the 1,463 instances of the corner vowels /i, u, a/ (step (5) in Figure 1).

The dependent variable was a measure of pitch computed as F0 or as F1-F0. Two types of fixed effects were included in the analysis. On the one hand, the variables of main interest in the present study: i.e. phonological vowel height ("high" vs "low") and hearing status ("normally-hearing (NH)" vs. "hearing-impaired (HI)"). On the other hand, two fixed effects were included as control variables to capture part of the variance in F0 that is assumed to be affected by the first consonant of the CVC (pseudo-)words [50] and by the duration of the vowel [51]. Two-way interactions between those predictors were also included. Random effects included random intercepts per child, as well as random slopes allowed for by the model construction.

The relatively small size of the HI sample in comparison with the NH sample resulted in an imbalance between groups. A bootstrapping procedure was implemented to mitigate sampling bias, randomly selecting the same number of children from each group, with replacement (see step (8) in Figure 1). By reducing the influence of the unbalanced sampling procedure, this bootstrapping approach aimed to provide a more accurate approximation of the observed effects, ideally asymptotically approaching their "true" values [52]. Additionally, it helped control for potential overfitting [47]. For further details, refer to [47, 52, 53]. The ceiling of the bootstrapping procedure was computed as the maximal number of unique combinations of *n* elements from a group of *k* elements in which each element could potentially occur up to *k* times based on formula (2) [54, p. 68]:

$$(2)\ \text{Ceiling} = (n+k-1)!/\ k!(n-1)!$$

Eventually, 6 children from the NH and HI groups were repeatedly selected in the bootstrapping procedure (step (8) in Figure 1).

This procedure generated a total of 5,005 bootstrapped samples, each consisting of 6 children from the hearing-impaired and normally-hearing groups.

The final model was then applied to each of these bootstrapped samples (step 9 in Figure 1). The estimates of the fixed effects were retained for each bootstrapped sample (step (10) in Figure 1) to construct confidence intervals unbiased by unbalanced sample sizes (step (11) in Figure 1).

Results

The present study addressed 3 main research questions: Do all children exhibit IF0 (**RQ1**)? Is IF0 different for hearing-impaired children and their typically hearing peers (**RQ2**)? And does device type affect IF0 differently in the three groups of children according to device type, i.e. normally-hearing vs. hearing-impaired fitted with a conventional hearing aid vs. hearing-impaired fitted with a cochlear implant (**RQ3**)?

The first analysis focused on IF0 in the entire dataset in order to answer the question **RQ1**. For this purpose, descriptive statistics of the F0 of high and low vowels produced by the three groups of children are shown in Table 3. The F0 was measured in Hertz and normalized to z-scores [40], meaning that the highest values on the Hertz scale are associated to positive values on the normalized scale, while low Hertz values are associated with negative normalized values.

The results showed that the F0 of high vowels was consistently higher than that of low vowels across groups. The first column of Table 3 highlights that high vowels had an average

F0 of 1.040 while low vowels had an average F0 of -1.486, resulting in an average distance of 2.526. For comparison, the F0 difference between the high and low vowels in the acoustic model presented to the children was 1.952, with an average F0 of 0.612 for high vowels and -1.340 for low vowels. These findings support the presence of IF0 in the speech of six-year-olds, indicating that vowel height influences F0 in this age group, consistent with existing literature on intrinsic vowel pitch.

	Full dataset		**NH**		**HA**		**CI**	
	mean	*SD*	*mean*	*SD*	*mean*	*SD*	*mean*	*SD*
High vowels	1.040	1.806	1.044	1.792	1.142	1.732	0.909	2.023
Low vowels	-1.486	1.409	-1.563	1.360	-1.017	1.663	-1.179	1.527
IF0	2.526		2.607		2.159		2.088	

Table 3: Descriptive statistics of the observed F0 measurements expressed in z-scores for high and low vowels as a function of hearing status.

To test the significance of the F0 difference between high and low vowels across all children regardless of their hearing abilities, a multi-level model was constructed. Stepwise model construction was employed to determine the most appropriate model for the data.

The stepwise model construction process resulted in the best-fitting model, which included the main effects of vowel height, the preceding consonant in the CVC stimulus, and vowel duration, along with two-way interactions between vowel height and the preceding consonant, as well as between vowel height and vowel duration. Additionally, the model incorporated random slopes for vowel duration and the preceding consonant (C1), as well as a random intercept per child. The results from the final model are presented in Table 4.

A significant main effect of vowel height ($E = 3.78$, $t = 8.86$, $p < .001$) was found indicating that high vowels exhibited a significantly higher F0 than low vowels. Significant main effects of C1 = /p/ ($E = 1$, $t = 4.84$, $p < .001$) and C1 = /t/ ($E = 0.72$, $t = 3.92$, $p < .001$) were also observed indicating a higher F0 following those consonants than after /l/. Additionally, significant interaction effects were also found between vowel height and C1 = /t/ ($E = -1.06$, $t = -4.4$, $p < .001$) and between vowel height and vowel duration ($E = -4.43$, $t = -2.28$, $p <.05$), indicating that the increase in F0 associated to high vowels was reduced when C1 was a /t/ rather than a /l/ and that the effect of duration on the F0 was more reduced when the vowel was high than low. These variables were included in the statistical modelling to better account for all the variance, but a detailed discussion of them is beyond the scope of this paper.

	estimate	std. error	t-statistic	df	95% CI		p-value
					LL	*UL*	
(Intercept)	-2.38	0.4	557.79	-5.97	-3.17	-1.6	<.001
Height High	3.78	0.43	1101.99	8.86	2.94	4.61	<.001
C1/p/	1	0.21	151.17	4.84	0.6	1.41	<.001
C1/t/	0.72	0.18	241.62	3.92	0.36	1.08	<.001
Vowel duration	1.3	1.63	380.01	0.79	-1.91	4.5	0.428
Height High:C1/p/	-0.16	0.2	1327.71	-0.79	-0.55	0.23	0.429
Height High:C1/t/	-1.06	0.24	1371.44	-4.4	-1.53	-0.59	<.001
Height High: Vowel duration	-4.43	1.95	1150.15	-2.28	-8.25	-0.62	0.023

Table 4: Results of fixed effects for the final model for RQ1 (reference categories: C1 = /l/ and Height = Low).

RQ2. addressed the effect of vowel height on F0 in relation to hearing status. For **RQ2.**, the HA and CI children were combined into a single group of hearing-impaired children. If hearing status influences the effect of vowel height on F0, a significant interaction between phonological vowel height and hearing status would be expected.

The descriptive statistics provided in Table 3 show that in the three groups high vowels had a higher F0 than low vowels. The high vowels of the NH group had an average F0 of 1.044 on the normalized scale, i.e. higher than the -1.563 average observed for low vowels in the same group of participants. The difference in normalized F0 between the two vowel categories was thus 2.607 for NH children, 2.159 for HA children and 2.088 for CI children.

The final statistical model included a main fixed effect of phonological vowel height, C1, and vowel duration. The model also included interactions between C1 and vowel height, between vowel height and vowel duration, but also between vowel height and hearing impairment. The model also included random slopes for vowel duration and C1, and a random intercept per child. The results of the final model are reported in Table 5.

The key findings include a significant main effect of vowel height ($E = 3.858$, $t = 9.063$, $p < .001$), indicating that high vowels had a higher F0 than low vowels. In addition, a significant interaction between hearing impairment and vowel height ($E = 0.48$, $t = 2.65$, $p < .01$) was found for low vowels, indicating that low vowels presented significantly higher F0 values in the hearing-impaired group (i.e. HA and CI children together) compared to the speech of the normally-hearing group. The effects of the control variables vowel duration and C1 and their interactions are reported in Table 5 but are not discussed further.

	estimate	**std. error**	**df**	**t-statistic**	**p-value**	**Bootstrapped 95% CI**	
						LL	***UL***
(Intercept)	-2.46	0.4	573.46	-6.17	<.001	-3.55	-0.12
Height High	3.86	0.43	1112.48	9.06	<.001	1.3	4.85
Height Low:Hearing impaired	0.48	0.18	705.08	2.65	.008	-0.07	0.98
Height High: Hearing impaired	-0.1	0.14	156.19	-0.67	.505	-0.52	0.35
C1/p/	1	0.21	151.85	4.85	<.001	0.42	2.03
C1/t/	0.71	0.18	246.91	3.89	<.001	0.06	1.35
Vowel duration	1.3	1.63	408.29	0.8	.425	-9.03	5.7
Height High:C1/p/	-0.15	0.2	1327.43	-0.77	.439	-0.91	0.51
Height High:C1/t/	-1.06	0.24	1370.89	-4.42	<.001	-2.19	-0.25
Height High:vowel duration	-4.39	1.94	1180.31	-2.26	.024	-8.77	6.97

Table 5: Results of the final model for RQ2 - F0. (reference categories: C1= /l/, Hearing = typical and Height = Low).

To address the issue of unbalanced sample sizes, with a higher number of control NH children than HI children, a bootstrapping procedure was carried out on the final model to reduce potential biases. The results of the key effects are visualized in Figure 2, which displays the distribution of estimates across all bootstrap samples. For instance, the upper panel labelled “Height High” shows the distribution of the estimates obtained from all the multi-level models based on the bootstrapped samples. The shaded area represents the 95% confidence interval for these estimates. As evident from the figure, all estimates were clearly positive, indicating that high vowels consistently had a higher F0 than the reference level (i.e. low vowels). Furthermore, the 95% confidence interval did not include 0, as indicated by the vertical black line. This suggests that the likelihood of the predictor having no effect or a negative effect is very low. This leads to the conclusion that there is a significant positive effect of vowel height on F0.

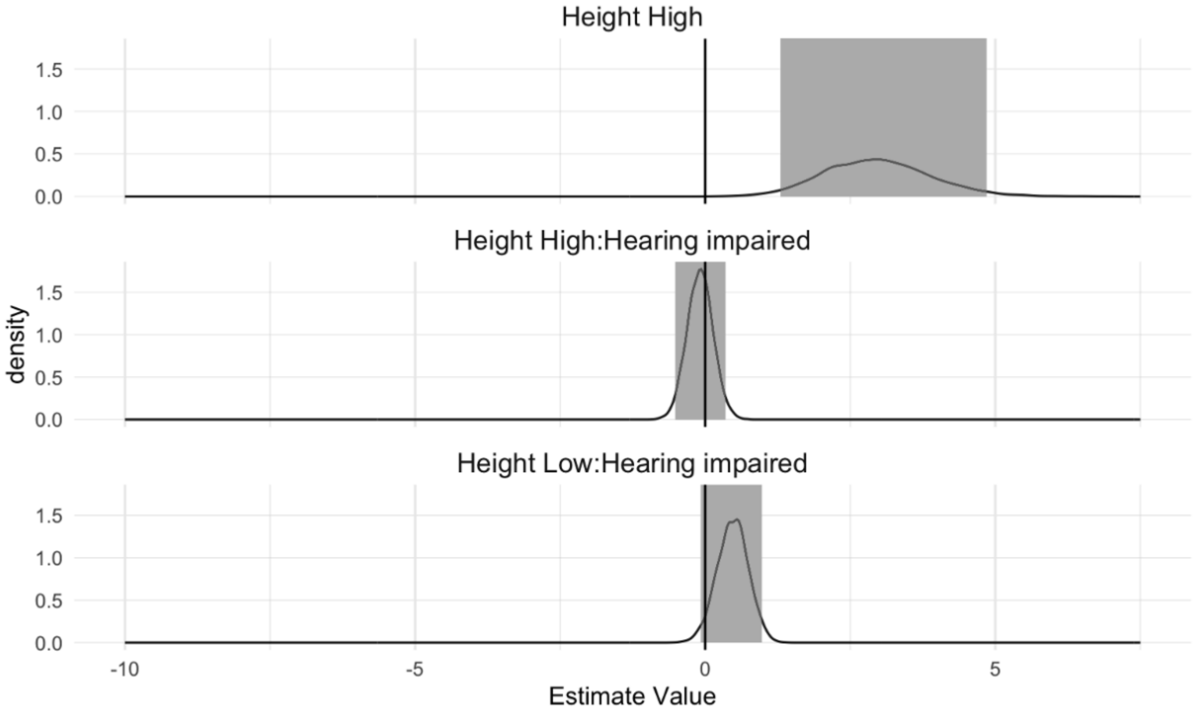

Fig. 2. Distribution of the estimates from all bootstrapped samples for fixed effect of interest in the final model with F0 as dependent variable (shaded area: 95% confidence intervals).

Compared to the previous analysis without bootstrapping, the bootstrapped results largely confirmed the earlier findings. Most importantly, the interaction between vowel height for high vowels and hearing status was not significant, meaning that both the NH and HI groups shared similar F0 for high vowels. The only divergence from the analysis without bootstrapping was that the interaction between vowel height and hearing impairment showed only a trend, as the bootstrapped 95% confidence interval slightly included 0, suggesting that low vowels tended to be higher in the hearing-impaired group, reducing the contrast between high and low vowels and, consequently, diminishing IF0. However, this trend was not statistically significant in the most conservative analysis with bootstrapping.

The bootstrapped confidence intervals for the other tested variables supported the previous analysis. The strongest observed effect was the fixed effect of vowel height, indicating that high vowels were associated with a higher F0 than low vowels. Most importantly, the interaction effect of vowel height for high vowels and hearing status remained non-significant, meaning that the NH and HI groups shared similar F0 for high vowels. Effects of the control variables and/or of interactions are reported in Table 5 but not discussed any further.

Through an alternative approach using F1-F0 instead of F0, this research investigated whether the interaction between vowel height and hearing status influenced this distance. Note that, a high F1-F0 value was expected for low vowels, since the F1 of high vowels is typically lower than that of low vowels. This implies that the F1-F0 distance of high vowels is smaller than that of low vowels. The final model (Table 6) included a fixed main effect of phonological vowel height, C1, vowel duration. It also included interaction effects between vowel height and C1, between vowel height and vowel duration, and additionally between vowel height and hearing impairment. The model also included random slopes for vowel duration and C1, and a random intercept per child. The results indicated a significant interaction between hearing impairment and vowel height (E = -0.55, t = -2.38, p = .018). Besides, the analysis revealed significant effects of vowel height (E = -6.08, t = -33.09, p < .001). The effects of the control variables (vowel duration and C1) are reported in Table 6 but are not discussed further.

	estimate	std. error	df	t-statistic	p-value	Bootstrapped 95% CI	
						LL	*UL*
(Intercept)	3.76	0.3	328.98	12.34	<.001	2.04	4.97
Height High	-6.08	0.18	1334.72	-33.09	<.001	-6.79	-5.02
Height Low:Hearing impaired	-0.55	0.23	157.02	-2.38	.018	-1.4	0.34
Height High: Hearing impaired	0.13	0.16	94.85	0.82	.413	-0.35	.65
C1/p/	-1.02	0.23	140.05	-4.51	<.001	-2.02	0
C1/t/	-1.07	0.19	196.5	-5.68	<.001	-1.84	-0.08
Vowel duration	2.5	1.21	169.14	2.07	.04	-2.49	8.84

Height High:C1/p/	0.29	0.21	1310.05	1.37	.171	-0.61	0.94
Height High:C1/t/	1.66	0.23	1370.37	7.34	<.001	0.38	2.73

Table 6: Results of the final model for RQ2 - F1-F0. (reference categories: C1 = /l/, Hearing = typical and Height = Low).

A bootstrapping procedure was also applied to this model. The results following bootstrapping are presented in Figure 3, which illustrates the distribution of the estimates for each bootstrap, along with 95% confidence intervals. The bootstrapped confidence intervals for the interaction effect between vowel height for low vowels and hearing impairment was not significant as the confidence interval included 0. Consistent with the previous findings, a substantial effect of vowel height on the F1-F0 distance was evident.

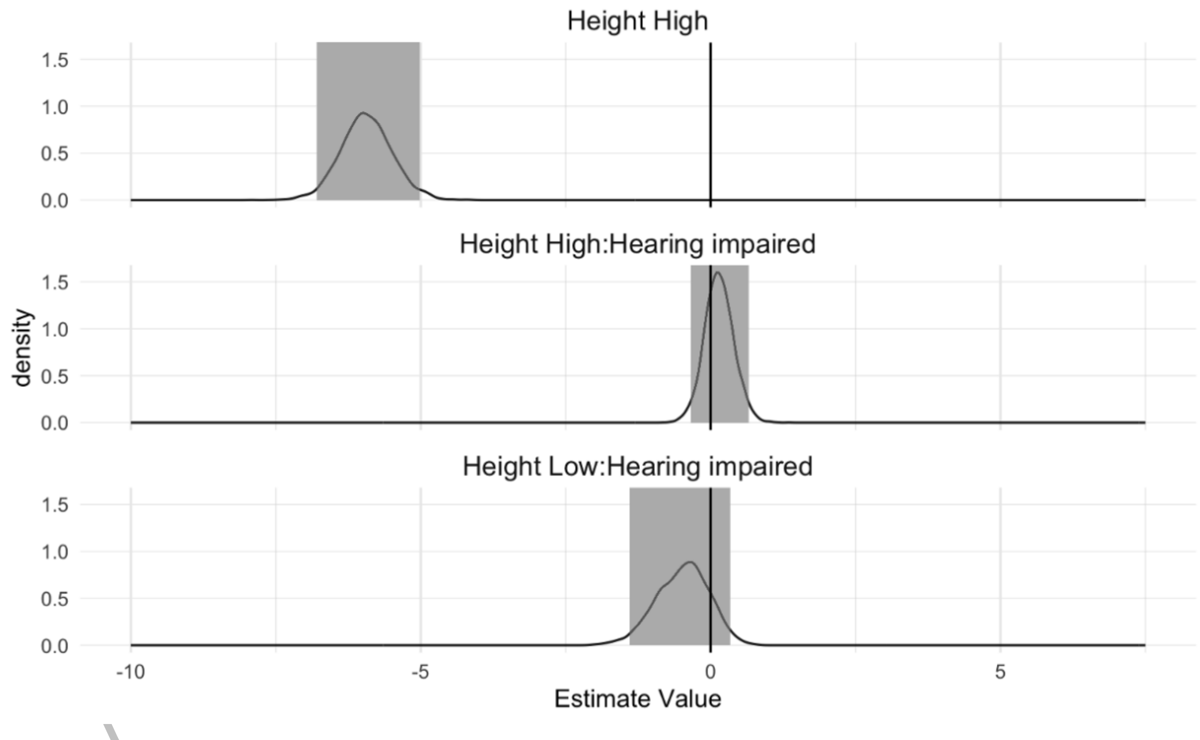

Fig. 3. Distribution of the estimates from all bootstrapped samples for fixed effect of interest in the final model with F1-F0 as dependent variable (shaded area: 95% confidence intervals).

While the previous analysis compared typically-hearing children with hearing-impaired children altogether, the analyses for **RQ3.** were designed to investigate whether similar effects were present among the three groups ("NH" vs "HA" vs "CI") in order to identify potential differences associated with the device type. The stepwise model construction revealed that incorporating the tripartite hearing status predictor did not enhance the model's fit with the data. This was true regardless of whether the dependent variable was F0 or F1-F0. This suggests that the previously observed differences between groups are specific to the NH and HI distinction, rather than between the NH, HA, and CI groups.

Discussion

This study investigated intrinsic vowel pitch (IF0) in two groups of speakers of Belgian Standard Dutch: a group of children with hearing impairment and a control group of age-matched children with typical hearing. The hearing-impaired children were further differentiated in terms of the hearing support they received by either a cochlear implant or a conventional acoustic hearing aid. IF0 expressed whether high and low vowels differed in F0. A large difference in fundamental frequency (F0) between high and low vowels indicated thus a large IF0 effect, a smaller difference in F0 between these vowel categories suggested a small IF0 effect. In the present study, IF0 was computed statistically as the effect of phonological vowel height on F0 (or F1-F0). However, other studies measure IF0 as the distance between vowel categories, typically expressed in Hertz or semitones, and use this distance as a dependent variable. Although those implementations of IF0 differ, research using both types of IF0 estimations are discussed in the following discussion.

Intrinsic vowel pitch in children with hearing impairment (RQ1)

The first finding was that all children exhibit IF0 regardless of their hearing status. The analyses showed that all five- to seven-year-old children produced the high vowels /i/ and /u/ with a statistically significantly higher F0 than the low vowel /a/. Although the statistical analysis was based on normalized data, average F0 values in Hertz and semi-tones are also provided for reference, as those scales are more convenient and familiar. The present study found that the average IF0 amounted to 30.659 Hz or 2.005 semi-tones. On the Hz-scale, this IF0 is substantially larger than the value for adults in Belgian Standard Dutch, i.e. 21 Hz [4], or in Netherlandic Dutch with an average IF0 of 21.5 Hz [55]. However, when expressed in semi-tones, the large IF0 observed in the high-pitch children speech is reduced and rescaled so that IF0 appears to be similar in size, with 2.28 in Belgian Standard Dutch [4] and 2.30 semi-tones in Netherlandic Dutch [55]. A higher F0 of high vowels in comparison with low vowels in children's speech is consistent with studies on adult speech (e.g., [3, 12, 13, 14], but see [9] for a study in which IF0 could not be documented). Thus, it can be concluded that IF0 is not only a feature of adult speech but that it is also characteristic of five-to-seven year old children's vowel production. This result aligns well with the findings reported in Whalen et al. [25] who found significant IF0 in babbling (but see Bauer [26]). These findings suggest that IF0 is a consistent feature across both children's and adults' speech, supporting the universality of IF0.

Size of intrinsic vowel pitch in children with and without hearing impairment (RQ2)

The second aim of this study was to compare the size of IF0 in children with hearing impairment and their typically-hearing peers. The analyses did not reveal significant IF0 differences between typically-hearing and hearing-impaired children. This result provides further support for the physiological hypothesis of IF0. Since the biomechanical link between the phonatory and articulatory systems remains intact in hearing-impaired children, it is expected that their IF0 would be similar to that of typically-hearing children. Had there been a statistically significant difference in the size of IF0 between groups, an explanation in terms of different perceptual abilities of HI and NH children would have been able to explain it. Yet, the fact that IF0 is similar in both groups does not refute the perceptual enhancement or physiological hypothesis.

The present study also controlled for potential differences in phonetic vowel height by analyzing the F1-F0 difference, further confirming that IF0 is consistent across both groups. This approach helped to eliminate the possibility that any observed between-group differences were the result of purely automatic phonetic processes. As such, the present study is the first to investigate IF0 in (hearing-impaired) children, while also controlling for differences in phonetic vowel height. This alternative methodological approach further confirmed that there were no significant differences between hearing-impaired children and their typically-hearing peers in terms of IF0. This finding also seems to align well with how Bush [27] interpreted her results. That is, there are no "qualitative" differences in how hearing-impaired children realize IF0, compared to typically-hearing children.

Nevertheless, it is worth mentioning that the present study revealed a trend towards a reduced IF0 in the speech of the hearing-impaired children. This trend may suggest an effect of hearing impairment on IF0, which could be accounted for by two alternative hypotheses. The first potential explanation could be that the degraded auditory input of these children hinders their ability to acquire IF0 as a means of enhancing phonological contrasts as early and/or as effectively as their typically hearing peers. This would imply that the contrast between high and low vowels may not (yet) be firmly encoded in terms of differences in F0. Alternatively, the smaller IF0 might result from the general difficulty of hearing-impaired children to control phonation (cf. [56, 57, 58]) regardless of their phonological knowledge. Irrespective of the cause – whether it is inadequate control over phonation or delayed integration of IF0 into their phonological system – such a trend would challenge the notion that IF0 is a purely physiological phenomenon.

It should also be noted that this trend is driven by the low vowels and not by the high vowels. According to the dual mechanism hypothesis [5], hearing-impaired children may produce a typical high F0 in high vowels by using the "tongue-pull" mechanism. However, they might not fully implement the "jaw-push" mechanism in low vowels. As a result, the F0 of low vowels would be lowered to a smaller extent in the hearing-impaired group than in the typically-hearing group. In fact, the "jaw-push" mechanism plays a more critical role in the production of low vowels compared to high vowels. Therefore, hearing-impaired children might produce similar high vowels, but different low vowels compared to their typically-hearing peers. The reasons for why hearing-impaired group differs only in the production of the low vowels remain unclear. One potential explanation could be that while the "tongue-pull" mechanism is physiologically constrained, further increasing the tongue-pull movement could result in an excessive occlusion in the oral cavity, impeding vowel production. In contrast, the jaw-push mechanism may offer more scope, allowing children to functionally employ this mechanism to further increase the distinction between high and low vowels. Hearing-impaired children may have difficulty reproducing the fine control over that specific mechanism. Due to the subsequent higher F0 of the low vowels, this could lead to a reduced IF0 effect.

Although this trend might seem intuitively divergent from that observed in Bush [27], the results of both studies could document the same phenomenon at different developmental stages. In fact, although the qualitatively IF0 effect was similar, the difference in F0 between high and low vowels appeared quantitatively larger in the hearing-impaired children than in the typically-hearing children in Bush [27]. This difference with the present study might be attributed to the more homogenous group of children in the present study, and most importantly, to the different age-ranges of the participants in Bush [27]. The present study included children between 5 and 7 years old, whereas Bush's study included children between 9- and 17-years-olds. The trend towards a smaller IF0 in younger children with hearing impairment might suggest that hearing impairment has an effect on IF0, but that this study may not capture this fully, as younger children might already have compensated for it and produce IF0 similarly to their typically-hearing peers. This could explain why Bush [27] did not observe a smaller IF0 effect. The older children in Bush's study might overarticulate, perhaps by trying to imitate the overarticulation they are exposed to in speech therapy or family interactions, as suggested by Baudonck's study on prelingually deaf children [59, p. 159]. This overarticulation could lead to a larger IF0 in hearing-impaired children. The difference between the observed trends at a younger age (the present study) or later (the study of Bush [27]) might point out at the potential role that (hearing) age may play in IF0, particularly if the perceptual or mixed hypothesis holds true.

Effect of device type on the size of intrinsic vowel pitch in children with hearing impairment (RQ3)

The descriptive data suggest that IF0 was smaller in the CI group compared to the HA and NH groups, aligning with the expectations of the perceptual enhancement hypothesis. However, modeling the HA and CI children as separate groups did not improve the model fit, possibly due to data limitations or because hearing impairment itself, rather than the specific type of device used, better explains the observed differences.

Implications for a theory of intrinsic vowel F0 and future directions

Overall, the study's findings are consistent with the physiological hypothesis of IF0, while also suggesting a possible role for perceptual factors. That is, the present data are most consistent with the physiological hypothesis (among others: [1, 16, 17, 18]), but do not firmly exclude the perceptual enhancement hypothesis and the mixed hypothesis. The consistent presence of IF0 across all children indicates that it likely arises as a by-product of vowel articulation, stemming from the biomechanical link between the articulatory and phonatory systems. While slight differences between hearing-impaired and typically-hearing children suggest a potential perceptual component, this study emphasizes that the observed trend should not be considered definitive evidence for a perceptual basis of IF0.

However, this trend suggests the need for further research, particularly longitudinal studies and/or studies of younger children’s speech. Such research could uncover perceptual effects which the present study may have missed because of its limitation to children of one particular age. By the age of 6, the hearing-impaired children may have already caught up with their typically-hearing peers. In addition, examining IF0 at several time points could also reveal developmental patterns in how the production of IF0 evolves in typically-hearing and hearing-impaired children. These patterns may well, be indicative of an underlying perceptual cause. Over time children may gradually learn to use IF0 as a way to enhance phonological vowel contrasts, beyond the IF0 effects that arise purely from physiological factors. This would be in accordance with earlier studies suggesting the combined effect on IF0 of physiology and perceptual enhancement (e.g. [4, 15]).

Therefore, longitudinal studies would be valuable to examine the development of (the size of) IF0 in the speech of children with and without hearing impairment. Such studies could be complemented by articulatory research. Future research could also explore how hearing age affects the development of (the size of) IF0 and whether the size of a language’s vowel inventory influences its acquisition.

Limitations

The present study attempted to shed light on the effect of hearing impairment on IF0 in the speech of 6-year-old children who are native speakers of Belgian Dutch. Several limitations of this study should be noted. Firstly, the speech samples were elicited in a repetition task rather than the children’s spontaneous speech production. While auditory stimuli in such tasks may influence children's productions, this influence would likely be consistent in size and direction for all the children irrespective of their hearing status.

Secondly, although the size of the speaker groups was balanced using a bootstrapping approach, the original sample sizes of the hearing-impaired groups were relatively small warranting cautious interpretation of the results. Furthermore, the methodology adopted made it necessary to remove some data from the original dataset in the final sample due to the very stringent, cautious and conservative method of data reduction. Future studies with more participants and more comprehensive data collection are encouraged. Moreover, longitudinal studies starting at a younger age could provide a more detailed understanding of speech development, including IF0, in age-matched typically hearing and hearing-impaired children. This would allow examination of whether the size of IF0 develops as a function language acquisition, which was not possible with observations collected at a single point in time.

It is also important to recognize the limitations inherent in the acoustic analysis of IF0. First, it implies that the F0 information is not directly captured at the laryngeal level, hence does not provide any direct information about the laryngeal source itself. Second, the F1 information is also collected in terms of formants by analysing the radiated sound and as such it does not provide direct information about the resonance frequency *per se*. Therefore, it would be valuable to complement acoustic analyses with articulatory studies to gain a better understanding of IF0. Furthermore, acoustic analysis can be challenging in speech characterized by high F0, as high F0 tends to lead to overestimation of F1 for high vowels and underestimation for low vowels [60, 61]. However, this effect is consistent across the studied population sharing similar pitch ranges. To address these challenges, future research should incorporate articulatory techniques alongside acoustic analysis. Nevertheless, any potential perceptual effect must be acoustically investigated, since the potential differences between high and low vowels that reach the listener's ear are transmitted through the radiated sound.

Conclusions

The current study investigated the relationship between IF0 and hearing impairment in six-year-old Dutch-speaking children, marking the first investigation involving a homogeneous group of age-matched children, unlike previous studies such as Bush [27]. The first key finding was that all children, regardless of hearing status, exhibited IF0, producing higher F0 on the high vowels than on the low vowels. This result aligns with the physiological hypothesis, which attributes IF0 to the biomechanical processes of speech production.

The second key finding revealed a trend suggesting that hearing-impaired children may have a smaller IF0 compared to their typically hearing peers. This suggests that IF0 may well have a perceptual component. A plausible explanation for this trend is that the delayed and reduced quality of the auditory input in hearing-impaired children might hinder their ability to precisely control F0, affecting their ability to enhance the contrast between high and low vowels. Alternatively, this contrast may not yet be firmly acquired as a phonological contrast encoded in terms of F0. Although this effect was not significant in the 6-year-old age group, the findings underscore the importance of further investigation, particularly in younger children, to gain a more detailed and comprehensive developmental picture of IF0.

In conclusion, while the results of the present study support the physiological hypothesis, they also suggest a potential role for perceptual factors in shaping IF0. Further investigation is needed to fully understand the interplay between physiological and perceptual influences on IF0.

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Statement of Ethics

Study approval statement: This study protocol was reviewed and approved by the Ethics Committee for the Social Sciences and Humanities of the University of Antwerp, approval SHW_21_48.

Consent to participate statement: Written informed consent was obtained from the parents (or legal guardians) of the participating children as well as from the school principal and the children's teachers.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Jérémy Genette: conceptualization, methodology, formal analysis, investigation, writing – original draft preparation. Steven Gillis: conceptualization, methodology, formal analysis, investigation, writing – review and editing, and supervision. Jo Verhoeven: conceptualization, methodology, formal analysis, investigation, writing – review and editing, and supervision.

Data Availability Statement

The data that support the findings of this study are openly available as supplementary material. Further enquiries can be directed to the corresponding author.

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