DOI: 10.61782/fa.2023.0675

forum acusticum 2023

# ACOUSTIC AND DEVELOPMENTAL FACTORS IN VOICE PERCEPTION IN CHILDREN WITH HEARING DEVICES

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## ABSTRACT*

Perception of voice cues, voice pitch (F0) and vocal-tract length (VTL), is important for recognizing speakers. Its investigation in children with hearing devices could be challenging due to the combined effects of cognitive development and distortions induced by hearing loss. We measured voice cue just-noticeable-differences (JNDs) in school-age children with hearing aids, cochlear implants, or typical hearing. Children with hearing aids had, overall, larger voice cue JNDs (less sensitive) than the control group, but this effect was mostly confined to younger ages for F0. Individual data showed relatively large overlap between the JNDs of typically-hearing children and those using hearing aids. For the few children with very large JNDs, the degree of hearing loss or aided thresholds did not seem determining factors. Children with cochlear implants in general had larger voice cue JNDs than the control group, while there was also some overlap with JNDs of the control group. Such overlap in adult CI users' JNDs with their own control group was smaller in comparison. In all children, general developmental effects were seen, although these differed between F0 and VTL perception. Overall, results confirm that early use of hearing devices can provide benefits in voice perception, and with continued use of the devices this ability may develop further.

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**Keywords:** *voice pitch, vocal tract length, hearing aids, cochlear implants, development*

## 1. INTRODUCTION

Perception of voice cues, such as voice pitch (F0) and vocal-tract length (VTL), help recognizing speaker characteristics, such as perceived gender, age and size [1]. In normal hearing, adults are sensitive to voice cues, and able to identify voice cue differences as small as 1 semitone (st; [1], [2]). In normal-hearing children, two studies investigated cognitive development effects on voice cue perception in differing child populations. The results showed that children could reach adult voice cue sensitivity levels around the ages of 8-11 years (Israeli children; [3]), but the developmental trajectories may differ, with F0 discrimination reaching adult levels at 12 years while VTL discrimination reaching adult levels at 8 years (Dutch children; [4]). In line with the different sources of the two voice cues, namely, F0 being closely related to glottal pulse rate and VTL to formants and spectral content, the observation by Nagels et al. [4] confirmed that the two voice cues are processed with distinct perceptual mechanisms.

Voice cue perception in children with hearing loss who use hearing devices may differ from that of children with normal hearing. In children with hearing aids, audibility and suprathreshold distortions related to hearing loss, such as reduced frequency selectivity or dynamic range, could potentially affect acoustic cues related to voice characteristics and reduce sensitivity to voice cues. Hearing aids provide sound amplification in a way designed to mainly improve speech perception [5]. While in adults with hearing loss some difficulties have been suggested in the perception of voice cues (e.g., using a paradigm of perception of speech in competing speech masker, [6]), it is not clear to what degree hearing aid features can compensate for hearing loss for voice perception in both children and adults.

In cochlear implants, distortions in transmitted voice and speech cues would be due to reduced spectro-temporal details caused by the limitations in electric stimulation of the auditory nerve [7]. In postlingually deafened and implanted adult users of cochlear implants, larger JNDs than normal hearing have been shown for both F0 and VTL discrimination [8], [9]. Fuller et al. further showed, using a task of perceived voice gender categorization, that adult implant users could make partial use of F0 cues but not VTL cues for the task [10]. Since VTL is more closely related to the spectral content of speech, this was explained by reduced spectral resolution in cochlear-implant speech perception. While the same limitations should also apply to child users of cochlear implants, there are a number of differences to adults in this population. Unlike adult implant users, children receive their implants before having had the chance to develop an acoustic auditory perception system, and they may benefit from neuroplasticity and adapt more effectively than adults to cochlear-implant transmitted speech. Hence, it is not clear if voice perception in implanted children would follow the patterns of that of implanted adults.

The studies presented in this paper aimed to assess voice cue discrimination in children with hearing aids or cochlear implants. To achieve this aim, voice discrimination for F0 and VTL was investigated in school- age children with hearing aids or cochlear implants. One potential difficulty in studying voice perception in children with hearing devices is that the results will not be only due to potential distortions in voice cues related to hearing loss-related factors, but they will also be affected by cognitive developmental factors [3], [4]. To tease apart developmental effects, comparable data were also collected from age-matched children with normal hearing for each test group, and for full characterization of developmental effects, also from adults with normal-hearing.

## 2. METHODS

The present study is part of a larger project, Perception of Indexical Cues in Kids and Adults (PICKA-TR).

### 2.1 Participants

For investigating voice cue perception in children with hearing aids, 55 children (5.4 - 17.8 yr) participated in the study as the experimental group. The children were all bilateral Phonak hearing aid users, with hearing losses varying from moderate to complete hearing loss (by classification based on WHO Report on Hearing [11]; complete hearing loss refers to a four-frequency based pure-tone thresholds, PTA4 ≥ 95 dB HL in better hearing ear). The participants had used their hearing aids for a minimum of six months. 86 age-matched normal hearing children participated as the child control group (6.0 - 17.1 yr), and 68 normal hearing adults (19.1 - 35.0 yr) participated to provide data for characterizations of voice cue perception development. Test and control participants were all native Turkish speakers.

For investigating voice cue perception in children with cochlear implants, 14 children (4.0 - 16.1 yr) participated in the study as the experimental group. The participants had used their cochlear implants for a minimum of one year. For comparison to children and adults with normal hearing, and for comparison to adults with cochlear implants, we used previously published data in [4] and [8], respectively. Test and control participants were all native Dutch speakers.

All participants, and in case of young children also their parents, provided written consent. Both protocols were approved by the respective onsite ethical committees.

### 2.2 Stimuli

The stimuli were prepared following the same procedures as in [8], in Turkish for the experiment with children with hearing aids, and in Dutch for the experiment with children with cochlear implants. In either version, first a number of consonant-vowel (CV) syllables were spliced from meaningful CVC words, then the stimuli were built by concatenating three random CV syllables forming a CVCVCV pseudo-word. During the experiment, for each trial, the same pseudo-word was used for the three presentation intervals, but one interval differed in the average F0 or VTL value, presented in an odd-one-out paradigm.

The voice cue manipulation was performed using STRAIGHT [12]. The average F0 was manipulated on F0 contour, and VTL on spectral envelope. To create a voice with a different F0, the average F0 of the CV triplet was lowered by a factor in st, as determined during the adaptive procedure. VTL was manipulated by shrinking the spectral envelope toward the lower frequencies.

### 2.3 Setup

All normal-hearing children and adults were tested in a relatively quiet room either at their school, home, or onsite, using headphones. Hearing-aided children were tested either in an audiology clinic room at Hacettepe University, or in a silent room at a hearing aid shop or rehabilitation center, using Logitech Z200 speakers. Cochlear-implanted children were tested in a relatively quiet room at home using Logitech Z200 speakers. During the experiment, all participants were seated in front of a touchscreen laptop and stimuli were presented at a sound level of 65 dB SPL.

### 2.4 Procedures

Voice cue discrimination was measured using the 3I-3AFC (odd-one out) and 2-down 1-up adaptive staircase procedure, reported by [8], and via the game-like interface used by [4]. In each trial, three identical sea animals, representing the three intervals, presented the stimuli sequentially with two same reference voices (not modified) and one odd voice stimulus (modified). The participants clicked on the the sea animal that corresponded to the odd stimulus. Visual feedback was provided in all trials. The initial step size was 2 st. After 15 consecutive trials with the same step size or when the difference became smaller than twice the step size, the step size value was divided by $\sqrt{2}$. The adaptive procedure was terminated after eight reversals and the geometric mean voice difference in st over the last six reversals was taken as the JND.

All participants could complete the test within 15 to 25 minutes and without a break.

## 3. RESULTS

### 3.1 Children with hearing aids

Figure 1 shows the JNDs for children with hearing aids, along with data from their corresponding controls of children and adults with normal hearing.

First, Figure 1 shows that the JNDs from Turkish children and adults improved as a function of age, indicating a developmental trajectory. Second, the JNDs of children with hearing aids were, overall, larger than the JNDs of the children with normal hearing. However, this effect seems mostly confined to younger ages, as the JNDs of children with hearing aids seem to overlap more with JNDs of age-matched children with normal hearing as the children. Individual data showed a relatively large overlap between the JNDs of children with hearing aids and children with normal hearing. The overlap seems larger for F0, since most JNDs from hearing-aided children fell in the 99% percentile, and many did fall between the 25% and 95% percentiles, with good overlap also on the median line. In contrast, for VTL, more JNDs of hearing-aided children were higher than 99% quantile, and almost all JNDs of hearing-aided children were at or higher than the median JND of normal-hearing children.

For the few children with very large JNDs, our preliminary analyses could not identify any clear explaining factor, such as the degree of hearing loss, i.e., the unaided hearing thresholds (shown), or the audibility, i.e., the aided hearing thresholds (not shown).

### 3.2 Children with cochlear implants

Figure 2 shows the JNDs for children with cochlear implants, along with data from their corresponding controls of children and adults with normal hearing (control data previously published by [4]). In addition, the JNDs from adult implant users, tested using a similar procedure and reported by [8], are also added.

Developmental effects in normal-hearing native Dutch speakers, also shown in Figure 2, were previously reported by [4]. The age effect on voice cue perception JNDs was significant, and children's F0 discrimination still differed from adults even at 12, the oldest age that was included in the study. In contrast, VTL discrimination was adult-like around the age of 8. We compared individual data of children with cochlear implants to the quantile percentage distributions based on control data. A large proportion of JNDs of cochlear-implanted children were above the median JND values of their NH age-equivalent peers. However, 9 out of 14 CI children had F0 JNDs and 4 out of 14 CI children had VTL JNDs within the 75% prediction intervals. The JNDs from adults with cochlear implants (data from [8], and reproduced in Figure 2) were all (except for one F0 JND point) outside the 90% prediction intervals based on JNDs from normal hearing adults. Hence, the JNDs of cochlear-implanted children seem to overlap more with JNDs of their own control group than those of cochlear-implanted adults with their own adult control group.

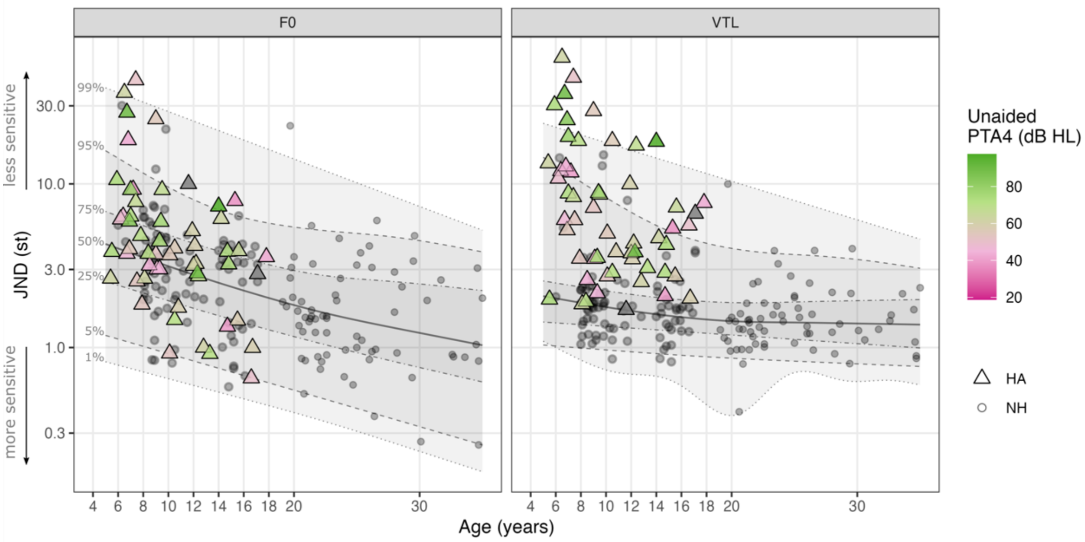


**Figure 1**. Voice cue JNDs shown for children with hearing aids as a function of age. F0 and VTL JNDs are shown in left and right panels, respectively. The triangles and circles show the data from children with hearing aids and from the control participants with normal hearing, respectively. The color coding on triangles indicates unaided PTA4s. The solid line shows the median (50th percentile) for control group, and the gray areas show the 1st, 5th, 25th, 75th, 95th, and 99th percentiles estimated based on a quantile regression analysis.

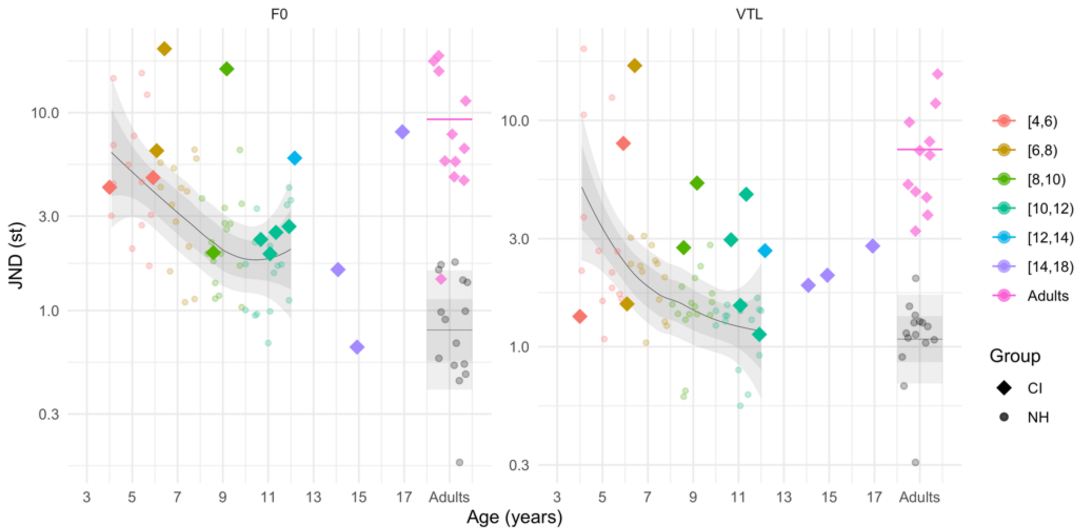


**Figure 2**. Similar to Figure 1, except voice cue JNDs are shown for children with cochlear implants (large diamonds), and color coded per age group, in a manner similar to the study by [4]. Data from control participants (circles) are reproduced from [4]. Data from adults with cochlear implants (small diamonds) are reproduced from [8]. Differently than Figure 1, the solid line shows the mean, with the gray areas showing the confidence intervals for the mean.

## 4. DISCUSSION

The purpose of the present study was to characterize voice cue perception in children with hearing aids and children with cochlear implants. Some aspects of voice perception (for example, recognition of unfamiliar voices [13] and voice similarity judgement [14]) had been shown to improve with age in normal hearing children, but perception of voice cues of F0 and VTL and its development is still a relatively new area. Based on previous work on voice perception in children in general, it was expected that voice cue perception would also likely develop in children, but it had not only been partially documented at what rate for F0 and VTL ([4]). The secondary purpose, therefore, was also to investigate the developmental trajectories in children with normal hearing and for a wide age range, for providing these as baseline references.

Our combined baseline data from Turkish and Dutch school-age children with normal hearing confirmed that there is a general age effect on perception of both F0 and VTL voice cues, however, with differing trajectories (also see [4]). F0 sensitivity seems to develop with a longer timeline in normal-hearing children than VTL sensitivity, which seems to reach adult-like sensitivity at an earlier age. Hence, to evaluate a specific hearing-aided child's voice cue perception with F0 or VTL, it is important to do so based on what would be expected for this child's age.

Once the developmental lines were established, we were able to evaluate the voice cue perception of children with hearing aids and children with cochlear implants. On a very positive note, using our adaptive procedures and presented with a game-like interface, all children, even the youngest ones tested (around 5 years old) could complete the test even though the test duration was long for some participants, around 25 min. The results from children with hearing devices showed that their voice sensitivity JNDs were in general larger than the JNDs of the control group with normal hearing, however, there were also more nuances.

For children with hearing aids, both voice cue JNDs were significantly larger than JNDs of the control group. This difference disappeared for F0 after a specific age but remained until adulthood for VTL. Differing developmental lines for different aspects of auditory perception is in line with previous studies with children with normal hearing [15] and children with hearing aids [16]. Individual data also showed that there was more overlap of JNDs of hearing-aided children with JNDs of normal-hearing children for F0 than VTL.

The distinct patterns in results with F0 and VTL may be related to differing perceptual mechanisms for the two voice cues. It is also possible that they are affected differently by hearing loss-related factors. The perception of voice cues could be affected by audibility, suprathreshold effects related to hearing loss and potential further changes that can occur due to hearing aids having to compensate for hearing loss. All of the children with hearing aids were fit by trained professionals, and were wearing well-fitting earmolds. Their aided thresholds were as expected and in general at recommended levels. As a result of inclusion of all healthy children with bilateral hearing aids, we did have a range of unaided and aided PTA4s. Using these, as an indirect check on potential audibility effects, we had conducted analyses, and found out that the variations in JNDs, especially for outlier JNDs, could not be explained by aided or unaided PTA4s. Hence, perhaps some suprathreshold effects, such as changes in frequency discrimination and spectral resolution [17], [18], and perhaps even in temporal resolution (as measured with gap detection; [19], [20]) and temporal fine structure [16], [21] could have differentially affected voice cue perception. Modern hearing aids offer many features to compensate for such suprathreshold deficiencies, however, to entirely compensate for perceptual effects from cochlear damage in hearing loss is not possible [22].

Audibility and potential suprathreshold effects could instantaneously affect the quality of the acoustic cues, however, there could also be effects from longer-term factors. The theory of Cumulative Auditory Experience [23]–[25] presents a nice framework for considering such factors. The theory postulates that the development of children with hearing loss could be affected by both past and present auditory exposure, as well as the language interactions of the children with other people. While we had not have the chance to explore such factors fully, we attempted to extract some relevant information from demographic questionnaires and data-logging of the devices that was available for some children. Data-logging confirmed consistent hearing aid use in the last six months before the testing data. If there was inconsistent hearing aid use before this period, as can be the case with younger children [25], [26], it was not possible to identify in this study. Data logging further showed, for the children where this information was available, the average hours of hearing aid use was relatively high (12.0 h/day). Hence, while voice perception sensitivity did not seem to correlate with unaided or aided thresholds obtained around the time of testing, we could not confirm or rule out other potential short-term or long-term factors.

For children with cochlear implants, in general, their JNDs were higher than the JNDs of their respective control group. This difference became smaller when the chronological age was replaced with hearing age, even though the group difference was still significant. What is perhaps more striking is that children with cochlear implants seem to have somewhat lower JNDs than the adults with cochlear implants, when they are compared to what would be expected for their age based on their respective normal-hearing control data. This observation is in line with some previous studies, but not all. Horn et al. observed more stable spectral ripple discrimination, a measure of spectral resolution, in children with cochlear implants when compared to adults with implants [27]. On the other hand, Deroche et al. observed the opposite in a different task, i.e., perception of F0 sweeps [28]. Our data show a large variation, and we had a relatively small number of implanted child participants, due to the very limited free time these children could have for joining our experiments. It is possible these limitations also apply to other studies with children with hearing devices, hence, more studies with new cohorts and perhaps also a range of auditory tests will be needed to establish these initial observations.

The differences we have observed in voice cue JNDs of implanted children and adults is mostly attributed to neural plasticity advantages in early ages (for a review, see [29]), which can lead to better perception and use of spectrotemporally degraded voice cues. On the other hand, there could be other factors that could have played a role. For example, the adult implant users who participate in our experiments tend to be older and while it is not yet clearly established with the paradigms we are using, based on other studies with F0 perception [30], there could be an aging effect on voice cue perception within adults with normal hearing or cochlear implants. Secondly, the children with implants reported in this paper were all bilateral users of cochlear implants, while the adult JND data were mostly from users of single cochlear implants. While the tasks that were used in the current study do not rely on sound localization or spatial unmasking, other advantages related to bilateral CIs, such as interaural differences, head shadow, and binaural redundancy, can lead to better access to environmental sounds [31]. These advantages, for example, could contribute to better incidental learning in children, and adding on to neural plasticity effects [32].

Overall, the results from both groups of children are promising. Many children with hearing devices can perceive voice cues, even if their devices are not necessarily developed nor optimized for voice perception. The data with implanted children and adults imply that children may benefit from neuroplasticity in early years. Further, all child groups show some developmental trajectories, and at least for F0 perception the JNDs of older children with hearing aids become similar to JNDs of their age-matched peers with normal hearing. These observations imply that children with hearing devices, with continued use of their devices, may further develop voice cue sensitivity.

## 5. ACKNOWLEDGMENTS

We are grateful to all children and their parents for their participation, clinical teams of UMCG and Hacettepe University for general support, and schools and hearing aid dispensers for their help with the recruitment of participants. We would also like to thank Iris van Bommel, Evelien Birza, Jacqueline Libert, Jemima Phillpot, Marta Matos Lopes, Paolo Toffanin, and Jop Luberti (illustrations) for their contribution to the development of the game interfaces.

## 6. FUNDING

This study is part of a research program funded by a VICI Grant from the Netherlands Organization for Scientific Research (NWO) and the Netherlands Organization for Health Research and Development (ZonMw) (Grant No. 918-17-603), Rosalind Franklin Fellowship by the University of Medical Center Groningen (UMCG), Center for Language Cognition Groningen (CLCG), the Scientific and Technological Research Institution of Turkey (TÜBİTAK Fellowship Grant 2214/A), and Heinsius Houbolt Foundation.

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