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Perception of voice cues in school-age children with hearing aids

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ABSTRACT:

The just-noticeable differences (JNDs) of the voice cues of voice pitch (F0) and vocal-tract length (VTL) were measured in school-aged children with bilateral hearing aids and children and adults with normal hearing. The JNDs were larger for hearing-aided than normal-hearing children up to the age of 12 for F0 and into adulthood for all ages for VTL. Age was a significant factor for both groups for F0 JNDs, but only for the hearing-aided group for VTL JNDs. Age of maturation was later for F0 than VTL. Individual JNDs of the two groups largely overlapped for F0, but little for VTL. Hearing thresholds (unaided or aided, 500–400 Hz, overlapping with mid-range speech frequencies) did not correlate with the JNDs. However, extended low-frequency hearing thresholds (unaided, 125–250 Hz, overlapping with voice F0 ranges) correlated with the F0 JNDs. Hence, age and hearing status differentially interact with F0 and VTL perception, and VTL perception seems challenging for hearing-aided children. On the other hand, even children with profound hearing loss could do the task, indicating a hearing aid benefit for voice perception. Given the significant age effect and that for F0 the hearing-aided children seem to be catching up with age-typical development, voice cue perception may continue developing in hearing-aided children.

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I. INTRODUCTION

The voice cues of fundamental frequency (F0) and vocal-tract length (VTL) help identify speaker-specific characteristics, such as talkers' perceived gender, age, and size information (Belin *et al.*, 2004; Skuk and Schweinberger, 2014; Smith and Patterson, 2005). They further support better segregation of speakers in multi-talker listening environments and improve intelligibility of speech in speech maskers (Başkent and Gaudrain, 2016; Darwin *et al.*, 2003).

In normal hearing (NH), adults seem remarkably sensitive to detecting small differences in voice cues. On short speech tokens, adults can detect F0 and VTL differences of about 5% (Başkent and Gaudrain, 2016; Smith and Patterson, 2005). In children, perception of voice in general develops during childhood, as shown for recognition of unfamiliar voices (Mann *et al.*, 1979), voice similarity judgments (Petrini and Tagliapietra, 2008), pitch and timbre perception (Saffran *et al.*, 2006), and perception of prosodic features (Nelson *et al.*, 1989). For perception of the voice

cues of F0 and VTL, Zaltz *et al.* (2020) investigated voice cue discrimination using three-word sentences manipulated either in F0, VTL, or both combined and reported that 8- to 11-year old children were able to use both F0 and VTL cues in a manner comparable to adults. Nagels *et al.* (2020) studied school-age children of a wider age range, 6 to 12 years, and using three-syllable concatenated speech stimuli. There were differences in voice cue discrimination between the children and adults, indicating developmental effects, and also differences in the developmental trajectories for F0 and VTL discrimination, indicating different perceptual mechanisms for each voice cue. Children's VTL discrimination abilities reached adult-like levels around 8 years, in line with the findings of Zaltz *et al.* (2020), while the F0 discrimination abilities at 12 years were still significantly different from those of adults.

In the case of cochlear hearing loss, the perception of F0 and VTL may be altered. This could be a direct result of the reduced access to relevant acoustic cues caused by elevated hearing thresholds and decreased hearing sensitivity. Additionally, sounds audible above the threshold levels could still be affected by suprathreshold factors related to hearing loss, for example, due to wider auditory filters (Van Tasell, 1993) that can reduce frequency discrimination and spectral resolution (Başkent, 2006; Moore, 1995), but also potential reductions in temporal resolution (Brennan *et al.*,

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2018; Reed *et al.*, 2009) and sensitivity to temporal fine structure (Halliday *et al.*, 2019; Moore, 2008). These effects may not be easily compensated for by hearing aid amplification, but additional features of hearing aids may help (Kates and Arehart, 2014; Souza, 2016). For example, while hearing thresholds are typically elevated in hearing loss, the maximum loudness levels remain similar to that of NH. This leads to loudness recruitment and reduced dynamic range as additional consequences of hearing loss (Buus and Florentine, 2002; Van Tasell, 1993). To provide the best audibility and to restore some natural loudness perception, hearing aids provide dynamic range compression. Such amplitude compression involves adjusting how much amplification will be applied to sounds of low or high intensity, thereby matching the wide dynamic range of the incoming sounds to the reduced dynamic range available in the impaired auditory system (Davidson and Skinner, 2006; Pittman *et al.*, 2014). All of the amplification settings and other features of hearing aids are designed in a way to best improve speech perception (Ching *et al.*, 2001; Launer *et al.*, 2016; Pavlovic, 1988; Tomblin *et al.*, 2015; Tomblin *et al.*, 2020). It is not clear to what degree this speech perception-oriented design and the hearing aid features can compensate for hearing loss as far as voice perception is concerned.

The effects of hearing loss and hearing-aid amplification on voice cue perception remain largely unknown. Most studies on voice cue perception in hearing loss have focused on adult cochlear implant users, who appear to have considerably larger discrimination thresholds. This was shown both in adult implant users who were implanted post-lingually (El Boghdady *et al.*, 2019; El Boghdady *et al.*, 2021; Gaudrain and Başkent, 2018; Nogueira *et al.*, 2021), and in adult implant users who were implanted early or post-lingually (Zaltz *et al.*, 2018). In particular, perception of VTL seems to be so severely affected that cochlear implant listeners seem to rely solely on F0 to categorize the perceived gender of a voice, whereas NH listeners rely on both cues (Fu *et al.*, 2005; Fuller *et al.*, 2014; Kovačić and Balaban, 2009). This voice cue perception deficit has been primarily attributed to the limited spectral resolution as a consequence of the physiological factors related to electric stimulation of the nerve by the cochlear implant (Başkent *et al.*, 2016; Gaudrain and Başkent, 2015, 2018). Whether the cause of changes in spectral resolution is through electrical stimulation via cochlear implants or due to widened auditory filters of hearing-impaired listeners, the functional consequences for voice cue perception may still be comparable. The few studies with hearing-impaired listeners have provided indirect evidence that F0 perception may indeed be altered in hearing loss. Arehart (1994) has shown altered patterns of complex-tone fundamental frequency discrimination in hearing loss. In follow-up studies, Arehart *et al.* (Arehart *et al.*, 1997; Arehart *et al.*, 2005) further showed that hearing loss may reduce the benefit of F0 voice cue difference between two vowels concurrently presented on double-vowel identification performance. Mackersie

et al. (2011) reported that hearing-impaired listeners benefited from differences in F0 cue between the target and masker speech for perception of speech in a speech masker, but not from differences in VTL cue. Zaltz and Kishon-Rabin (2022) measured voice cue discrimination in an older adult population with minimal hearing loss for their age for their age. Even within this small range of hearing loss, F0 and VTL cue discrimination seemed to be related to the degree of hearing loss (as was quantified by PTA4 [pure-tone average of hearing thresholds, across ears or the better ear, at four audiometric frequencies between 500 and 4000 Hz]).

In children with hearing loss, developmental factors and potential benefits from neuroplasticity may help partially compensate for detrimental effects from hearing loss. Children with cochlear implants, despite the limitations imposed by the electrical stimulation, tend to show F0 and VTL discrimination thresholds that are much smaller (higher sensitivity) than those of adult implant users (Nagels *et al.*, 2024). In fact, many child cochlear-implant listeners in the Nagels *et al.* study showed discrimination thresholds for F0 that were not distinguishable from their NH age-matched peers. For VTL, however, while most of the children of the cochlear implant group showed smaller thresholds than the adult implant users, they still demonstrated enlarged VTL discrimination thresholds compared to their age-matched peers. Zaltz *et al.* (2018) investigated the benefits of early implantation on F0 and VTL voice cue discrimination with prelingually deaf adults in two groups of participants: those who were early implanted (up to 4 years of age) and those who were late implanted (6 years of age or older). Early implantation was particularly associated with better VTL perception. Similarly, in children with hearing loss, in addition to the elevated thresholds and potential suprathreshold effects that would be directly relevant at the time of testing, other factors related to the past auditory experience before the time of testing may also affect voice cue perception abilities. According to the theory of cumulative auditory experience (McCreery and Walker, 2022; Moeller and Tomblin, 2015), the development of children with hearing loss would be affected by both past and present auditory exposure and language interactions. More specifically, this theory suggests that, in addition to maximizing access to sounds via a good fitting of hearing aid amplification settings, use of hearing aid features (remote microphones, noise reduction), the duration and consistency of hearing aid use, and the quality and quantity of the linguistic input and interactions in daily environments could also all affect the accumulated auditory experience, and these all could be modified to maximize the benefit. Halliday *et al.* (2019) investigated frequency selectivity and sensitivity to temporal fine structure or envelope cues in bilaterally hearing-aided children between the ages of 8 and 16 years and with mild to moderate sensorineural hearing loss. Both frequency selectivity and temporal fine structure sensitivity were reduced in children with hearing aids compared to the age-matched control group with NH. The differences

between the two groups were observed for all ages and for both aided and unaided test conditions. Flaherty *et al.* (2021a) conducted a study with bilaterally hearing-aided children between the ages of 9 and 17 years and with mild to severe hearing loss. The authors measured both F0 discrimination and the benefit from F0 difference between the target and masker speech in perception of speech in a two-talker masker. The hearing-aided children were able to derive benefits from large differences in F0 between the target and masker speech during speech-on-speech tasks, and both F0 discrimination and the F0 difference benefit showed a developmental effect. Yet, the F0 difference benefit was smaller when compared to age-matched children with NH. The F0 benefit was not significantly correlated with unaided PTA4, used as a proxy of degree of hearing loss, or aided PTA4, used as a proxy of access to acoustic cues with the hearing aid. The only significant correlation was with low-frequency pure-tone average (LFPTA [i.e., average of hearing thresholds at frequencies of 250 and 500 Hz]). No previous study has directly measured VTL perception in children with hearing aids; however, some indirect data are available from studies on spectro-temporal modulation detection (Kirby *et al.*, 2015; Kirby *et al.*, 2019) and second formant (F2) perception (Halliday *et al.*, 2019). VTL perception relies on perception of spectral profile of speech, and hence, perception of changes in formants (Ladefoged and Broadbent, 1957), and similarly, spectro-temporal modulation detection is considered to reflect a measure of spectral resolution (Henry *et al.*, 2005). The results from the studies by Kirby *et al.* (Kirby *et al.*, 2015; Kirby *et al.*, 2019) showed that ripple thresholds of children with hearing aids were lower than the thresholds of children with normal hearing; however, both groups showed a developmental effect. A correlation between the ripple thresholds and aided audibility, measured with the Speech Intelligibility Index (SII) (ANSI, 1997), was observed in one of the studies (Kirby *et al.*, 2015), but not the other (Kirby *et al.*, 2019). Similarly, Halliday *et al.* (2019) found that the two groups differed on average in F2 sensitivity, and while both groups showed a developmental effect, F2 sensitivity in hearing-aided children was less affected by age than in the NH group. Overall, previous research with child populations with varying hearing statuses and with different tasks potentially related to voice cue perception provides some indication that both F0 and VTL perception may be challenging in children with hearing aids, but there may be developmental effects. If such effects exist, these are important to know so that any challenge in voice cue perception could be evaluated based on what could be expected at that particular age, but also, perhaps development in childhood will help overcome this challenge to some degree, even if it comes with some delay.

In this study, we investigated voice cue perception in school-aged children with hearing aids to provide a comprehensive overview of voice cue perception for both F0 and VTL and also as a function of age. Specifically, we measured sensitivity to F0 and VTL cues in children with

bilateral hearing aids and with a wide range of degrees and configurations of sensorineural hearing loss, to ensure an as large representative population as possible. To characterize developmental factors, the data were analyzed in comparison to data collected from children and adults with NH.

II. METHODS

The present study is the first experiment of a larger project, Perception of Indexical Cues in Kids and Adults in Turkish (PICKA-tr), where voice and speech perception is investigated in children with hearing aids. The PICKA-tr project includes four experiments: voice cue discrimination (reported here), voice gender perception, vocal emotion recognition, and speech perception in speech maskers. The specific test used in this experiment is based on previous studies (Gaudrain and Başkent, 2015, 2018; Nagels *et al.*, 2020), with small modifications. The stimuli used in this study are in Turkish, as opposed to Dutch that was used in those studies, and the test population is children with hearing aids, as opposed to children and adults tested with cochlear implants or cochlear-implant simulations.

A. Participants

To achieve a good representation of varying levels and configurations of hearing losses, we designed the study to be as inclusive as possible, inviting all healthy children who use bilateral hearing aids to be participants. The test participant group included 55 hearing-aided children (age range = 5.4–17.8 years, mean = 10.3 years, standard deviation [SD] = 3.5 years). The control participant group included 86 age-matched normal-hearing children (age range = 6.0–17.1 years, mean = 11.0 years, SD = 2.9 years). The control data were used for characterization of voice cue discrimination development with normal hearing and in group comparisons. The adult control participant group included 68 NH adults (age range = 19.1–35.0 years, mean = 24.9 years, SD = 4.6 years). The adult data were used for the estimation of the age of maturity of voice cue discrimination in normal hearing.

Child participants were recruited via primary schools, the Hacettepe University Audiology Clinic, private hearing aid shops, rehabilitation centers, and the general public. Adult participants were recruited from Hacettepe University students and the general public. Inclusion criteria for all participants were being a native Turkish speaker, having self- or parent-reported normal or corrected vision, and having no diagnosis of neurological, developmental, motor, or language disorders. Inclusion criterion for the NH groups was having hearing thresholds of ≤ 20 dB hearing level (HL) at the audiometric frequencies of 500, 1000, 2000, and 4000 Hz. Inclusion criteria for the hearing-aided group were having bilateral sensorineural hearing loss (of any severity) and use of bilateral hearing aids for a minimum duration of 6 months.

The study was approved by The Clinical Research Ethical Committee of Hacettepe University, Turkey,

2019/07–22 (KA19038). For normal-hearing children, permission was obtained from the Turkish Ministry of Education to test the children at specific schools.

B. Demographics of child participants

Participants and parents filled out a demographic questionnaire, on age, education, music education, socioeconomic factors, spoken languages, general health, hearing health history, and hearing status. For children with hearing aids, hearing and hearing aid related information was collected both by the demographic questionnaire as well as by consulting parents where needed. There were some similarities in demographics between the hearing-aided and NH children, such as in age, education level of children (all children were students of state schools), socioeconomic background, and music education. (No child received any additional lessons other than what is offered at school, approximately 1 h/wk.) There was some variation in maternal education level within and between the groups (hearing-aided children, university, $N=8$, high school, $N=10$, primary school, $N=32$, unknown, $N=5$; NH children; university, $N=60$, high school, $N=23$, primary school, $N=2$, unknown, $N=1$). The difference in maternal education level is perhaps a result of the differences in recruitment, where children with NH were predominantly recruited via the network of colleagues and acquaintances of the co-authors, while children with hearing aids were primarily recruited via clinical care centers.

C. Demographics of children with hearing aids and hearing aid characteristics

For children with hearing aids, the inclusion criteria resulted in a participant group with moderate to profound hearing loss. The etiology for hearing loss, based on parental reports, included congenital and acquired hearing loss and one case of ototoxicity; however, also a number of parents could not provide such information. Some hearing aid settings for a sub-group of children could be extracted via the fitting software. This was only possible if there was sufficient time and if the child was tested at a location where such extraction was possible. To gather information regarding potential speech and language difficulties, we included a specific question in the questionnaire (“Disleksi, konuşma gecikmesi, kekeleme, belli harfleri-kelimeleri söylememe gibi dil veya konuşma problemi var mı? Eğer öyleyse, lütfen belirtin.”/“Does your child have language or speech problems, such as dyslexia, speech development delay, stuttering, or difficulties in pronouncing certain letters or words? If so, please specify.”). In their responses, the parents did not indicate any major specific speech and language problems, other than what could be expected and associated with hearing loss for the hearing-aided children. Furthermore, there were no known instances of auditory neuropathy spectrum disorder (ANSD) in our cohort. The universal hearing screening program in Turkey has greatly contributed to efficient screening and diagnosis of ANSD cases, and a

diagnosis of ANSD would have been documented in the participants’ medical records or reported by parents in the demographic questionnaire. However, no ANSD cases have been reported in the current study.

For the unaided audiometric thresholds, of the $N=55$ hearing-aided child participants, a total of $N=53$ children’s thresholds were available from their medical records (Fig. 1, upper panels). For the classification of the degree of hearing loss, we used the latest Hearing Report of World Health Organization (World Health Organization, 2021),¹ namely, based on PTA4, mild (20–35 dB HL), moderate (35–50 dB HL), moderately severe (50–65 dB HL), severe (65–80 dB HL), and profound (80 dB HL or greater). Based on this classification, the degree of hearing loss within the 53 hearing-aided children was moderate for $N=11$, moderately severe for $N=23$, severe for $N=15$, and profound for $N=4$. For the aided audiometric thresholds, $N=35$ children’s thresholds were available from their medical records (Fig. 1, lower panels).

All hearing-aided children were users of bilateral Phonak hearing aids (Phonak, Aurora, IL) with different models (Sky, $N=38$; Naida, $N=10$; Bolero, $N=4$; Audeo, $N=3$). Most children used behind the ear (BTE) type hearing aids ($N=52$; receiver-in-canal, $N=3$), and had been fitted with the DSL-V5 prescriptive algorithm (DSL-V5, $N=50$; NAL-NL2, $N=1$, Adaptive Phonak, $N=1$; Unknown, $N=3$), extracted from the clinical software. For $N=53$ children, the onset age of hearing aid use was available from the demographic questionnaires. $N=52$ children had started using their hearing aids at 10.0 years of age or younger, with an average onset age of 3.6 years (range = 0.25–10.0 years, SD = 2.5 years), and one participant started using their hearing aids from 16.0 years of age. The duration from onset use of hearing aids varied (range = 0.9–14.6 years, mean = 6.4 years, SD = 3.6 years). For $N=28$ children, the data logging feature was enabled, and the mean daily use of hearing aids was extracted using the clinical software. $N=26$ out of 28 children, for whom we had access to data logging, used their hearing aids 7.0 h or longer per day, with an average of 12.0 h/day (range = 7.4–15.8 h/day, SD = 2.5 h/day). The daily hearing aid use of two participants was significantly lower than the rest of the children, at 2.3 and 0.4 h/day. A closer inspection revealed that one of these participants had temporary battery problems. The other participant had relatively good hearing (thresholds around 10–25 dB HL) at lower frequencies up to 1000 Hz in their better ear and used their hearing aids when needed.

D. Stimuli

The stimuli consisted of three consonant-vowel (CV) syllables, forming a meaningless CVCVCV triplet (for example, “*şu-da-kü*,” “*ga-di-ta*”). The CV combinations were prepared to have a sample of sound combinations from the Turkish language, using procedures similar to those of

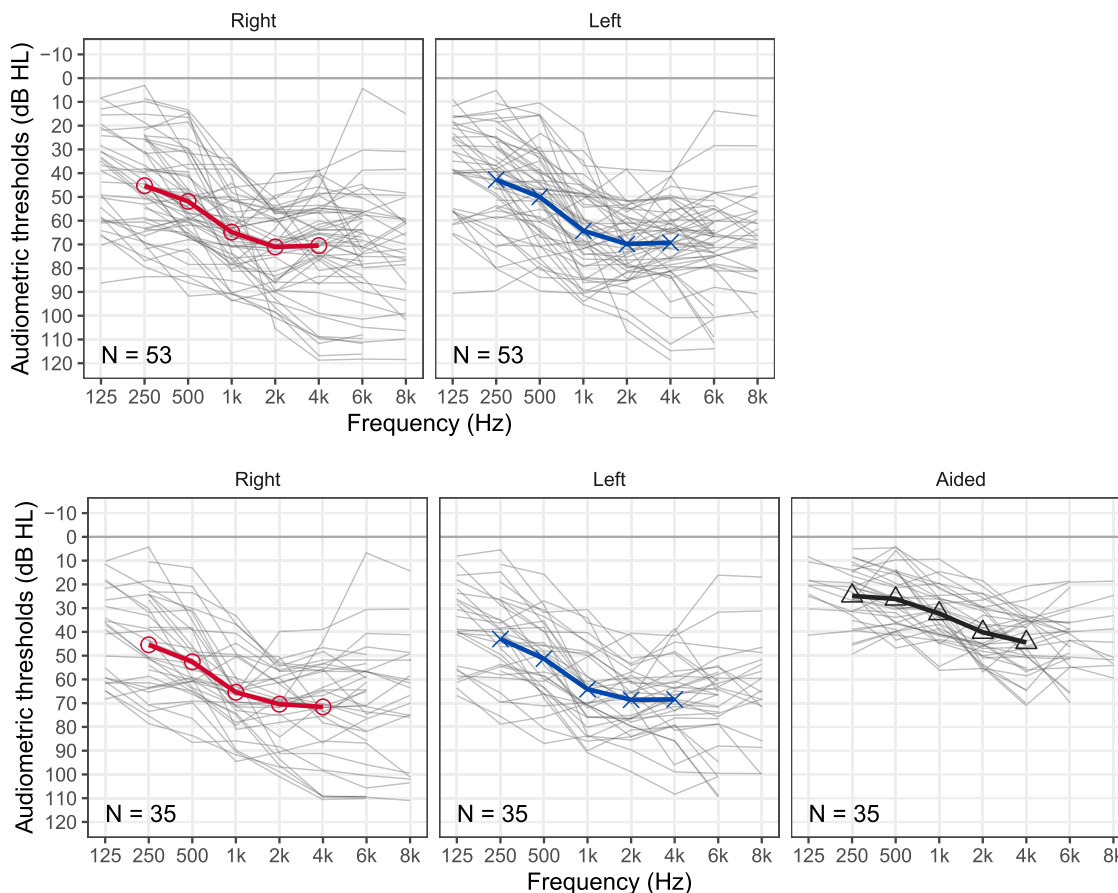


FIG. 1. (Color online) Unaided and aided audiometric thresholds are shown for the hearing-aided children where this information was available from the medical records. The upper panels show the unaided audiometric thresholds, separately for the right and left ears (left and right panels, respectively; $N = 53$ children). The lower panels show the unaided audiometric thresholds for the right and left ears (left and middle panels, respectively) and aided audiometric thresholds averaged across ears (right panel; $N = 35$ children). The thin gray lines in each panel show the individual hearing thresholds, while the thick red, blue, and black lines indicate the group mean thresholds of the right ear, left ear, and both ears, in panels from left to right, and only for a subset of frequencies (250 to 4000 Hz) where the thresholds were available for all children.

Gaudrain and Başkent (2015, 2018) and Nagels *et al.* (2020).

First, we prepared a list of meaningful Turkish CVC words that cover combinations of the Turkish vowels and consonants (except for one, soft g/\check{g} , due to its lack of distinct acoustic characteristics, Ünal-Logacev *et al.*, 2019). The words were chosen to be relatively common words, such as “bal” (honey), “küp” (cube), and “pul” (stamp), and reflected some frequency effects for the Turkish language (Örücü, 2009).² The word list was recorded from three female talkers with the following characteristics: (i) a 34-year-old adult female, 163 cm in height, with a mean F_0 of 213 Hz (range = 196–238 Hz); (ii) a 29-year-old adult female, 166 cm in height, with a mean F_0 of 201 Hz (range = 189–223 Hz); (iii) a 34-year-old adult female, 172 cm in height, with a mean F_0 of 217 Hz (range = 204–237 Hz). The mean F_0 values of each talker were extracted using PRAAT (version 6.2.17) (Boersma and Weenink, 2011). The estimated VTLs of the talkers were 13.5 cm, 13.6 cm, and 13.8 cm, respectively, based on their heights (Fitch and Giedd, 1999). Similar to procedures of Gaudrain and Başkent (2015), the word list was reduced to produce a list of CV syllables covering a good representation

of typical Turkish CV transitions. The CV syllables were then spliced from the selected word recordings using ADOBE AUDITION (Adobe Systems, San Jose, CA), to produce 78 CV syllables that were equalized in root mean square (RMS) intensity, and resampled to 44.1 kHz, 16-bit resolution. The CV syllables are made publicly available for research purposes (the link is provided in the Data Availability statement). The CVCVCV non-words were made by concatenating 3 CV syllables randomly selected from the 78 CV syllables.

We initially intended to precisely replicate the procedures of Gaudrain and Başkent (2015, 2018) and Nagels *et al.* (2020), where a single talker was used for all items. However, following an error in the labeling of the recordings during transfer between sites, the recordings from three different female talkers became mixed together in one set. The error remained unnoticed until data collection was completed, mostly because the three talkers have very similar voices and no discernable regional accents. This error may cause measured just-noticeable differences (JNDs) to be slightly larger than those observed in previous studies. However, because of the odd-one-out design used for this experiment, and because the error affected all trials for all participants, we do not expect that it would have

consequences on the comparison between groups, or on the observed effect of age. This is further discussed in Sec. IV.

E. Voice manipulation

The manipulation of the F0 and VTL cues of the stimuli was performed using STRAIGHT (Kawahara and Irino, 2005), implemented in MATLAB (MathWorks, Natick, MA). STRAIGHT decomposes the sound into its F0 contour, spectral envelope (as a function of time), and spectro-temporal aperiodicity map. The F0 contour was manipulated to alter the average F0, and the spectral envelope was manipulated to alter the VTL (see details below). The stimuli were then resynthesized with STRAIGHT using a pitch synchronous overlap-add method.

To create the reference voice, the average F0 of the original voice was adjusted to 242 Hz in order to match the average F0 of the speaker of the original recordings of the Dutch version (Gaudrain and Başkent, 2015, 2018; Nagels et al., 2020). The target voice was then produced from the reference female voice by lowering the F0 or lengthening the VTL, making the target non-word sound more male-like. For the F0 manipulation, the F0 contour was multiplied by a specific factor rather than shifting it by a number of hertz, in order to preserve the original F0 fluctuations and adjust the mean F0. In addition, the average F0 of each individual CV syllable was adjusted to also impose a small F0 contour within the non-word in order to improve the naturalness of the stimuli. This contour was made in random steps of 1/3 semitones (st), which could be $-1/3$ st, 0 st, or $+1/3$ st. Following this step, in order to ensure that the overall average F0 was unaffected, the overall F0 contour deviation of the CVCVCV nonword was centered to zero again. For VTL manipulation, the spectral envelope was shrunk towards the lower frequencies, by rescaling the frequency axis of the spectral envelope to shift all frequencies (and hence the formants too) by a fixed number of st. This st shift corresponds to a ratio that is the inverse of the ratio between the new and original VTL values. For instance, an increase in VTL of 4 st—or 1/3 octave—results

in a shift of all the formants of 4 st towards the low frequencies. Since 4 st corresponds to a ratio of 1.26, this means that all the formant frequencies are *divided* by 1.26. Illustrations of the voice cue manipulations are provided in the supplementary materials of Koelewijn et al. (2023).³

F. Procedure

Prior to data collection, all participants and parents of child participants were given detailed information about the study, their written informed consent was obtained, and parents and participants filled in the demographic questionnaire.

The same voice cue discrimination test and the child-friendly interface (Fig. 2) were used as the study reported by Nagels et al. (2020). The test measured the smallest voice cue difference a participant can hear, namely, the JND. The F0 and VTL JNDs were evaluated using a three interval, three alternative forced choice (3I-3AFC; namely, the odd-one out paradigm) adaptive staircase procedure. A short training was provided in two training blocks, one for each voice cue of F0 or VTL and each with three trials. Following the training phase, the test phase started, where experimental data were collected in one block for F0 and one block for VTL, in a randomized order. In both the training and test phases, a game-like visual feedback was provided, to make sure that children correctly understood and executed the task and the participants’ attention, especially that of the younger ones, is well maintained.

In the adaptive test, in each trial, the participants were presented with three stimulus intervals, each with the same (newly made for the trial) CVCVCV non-word, but one manipulated in average F0 or VTL (target interval) and differing from the other two (reference intervals with original F0 and VTL). Using the child-friendly interface, the stimuli were presented such that each of the three sea animals in the bottom (starfish in the example given in Fig. 2) produced one of the three CVCVCV non-words—either the target or one of the two reference intervals. The presentation order of the target non-word was random and could be at any of one



FIG. 2. (Color online) The child-friendly interface of the voice cue discrimination test. The illustration was made by Jop Luberti for the purpose of the study reported by Nagels et al. (2020) and published under the CC BY NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>).

of the three intervals, producing the three alternatives for the responses. The participants were asked to select the sea animal that produced the odd sounding voice (the target non-word) by clicking on it via the touchscreen of the test laptop. If the participants correctly responded, sea animals moved to take place in a circle around the big fish in the middle. If the participants incorrectly responded, a red square warning appeared, and the sea animals did not move. After the visual feedback, the experiment proceeded with a new trial with a newly made non-word, used for a new set of the target and reference stimuli.

The staircase of the adaptive test was implemented with a 2-down 1-up adaptive rule, to obtain JNDs yielding a 70.7% discrimination performance on the psychometric function, based on the adaptive psychophysical procedures described in detail by Levitt (1971). This performance level was chosen following previous studies with similar designs (Buss *et al.*, 2017; Nagels *et al.*, 2020), so that the results are comparable, but also because it provides an optimal level of operation. If a lower performance level is chosen, the task may become too difficult, especially for children, and if a higher performance level is chosen, the performance is too close to the ceiling, leaving no sufficient room to observe effects of experimental manipulations and individual variations. Each adaptive test started with a voice cue difference of 12 st in F0 or VTL between the target and reference voices. According to the adaptive rule 2-down, if the participant provided two correct responses consecutively, the voice cue difference was *decreased* by one step size. Conversely, for 1-up, if the participant provided one incorrect response, the voice cue difference was *increased* by one step size. Each change from up to down or down to up is a reversal. It is common to reduce the step size as the adaptive test proceeds and the voice cue difference starts approaching the JND value. The initial step size was 2 st to obtain rapid convergence towards the JND range. Yet, as the adaptive test proceeds, a smaller step size is desired to obtain greater accuracy. To that end, either after every block of 15 trials, or when the difference in the voice cue became smaller than twice the step size, we divided the step size by $\sqrt{2}$. This latter rule ensured that the F0 or VTL difference never crossed the zero line and became negative. The value of $\sqrt{2}$ was chosen so that two consecutive step-size reductions would result in dividing the step size by 2. The adaptive procedure was terminated after eight reversals, and JNDs were calculated by the geometric mean of the voice cue differences in st at the last six reversals. Depending on the participants' responses, between 18 and 106 trials were completed within each adaptive test. Most participants performed one adaptive test per voice condition (F0 and VTL), except for nine adult participants with NH who performed two tests per voice condition and one adult participant with NH and one hearing-aided child who completed two adaptive tests for VTL. For these participants, the average of the two measured JNDs were taken for further analysis. The demographic questionnaire took 3–4 min to complete. The overall duration of the complete PICKA-tr test battery was 50–60 min. The voice cue

discrimination test was 15–25 min without a break. All stimuli were presented at a presentation level of 65 dB sound pressure level (SPL).

G. Experimental setup

The testing locations and experimental setup differed slightly across participant groups, in an attempt to maximize inclusion and to obtain a relatively large number of participants. For all participants, we aimed to conduct the test at a convenient location and in a room as quiet as possible within that location. For NH children, we obtained special permission from the Turkish Ministry of Education to test the children at specific schools in as quiet a room as possible, such as the school library, as well as at their homes. For NH adults, we tested them at the Hacettepe University, in an audiometric soundproof room. Hearing-aided children were tested in an audiometric soundproof booth at the Hacettepe University, a hearing aid dispenser, or a rehabilitation center, which provides support for children with varying hearing status and deafness. The flexibility of testing location for this group allowed the hearing-aided children to be tested at a convenient time and location for them, for example, while they were visiting for their regular checks for their hearing and hearing aids.

Audiometric screening was conducted using an AS608B portable screening audiometer (Interacoustics, Middelfart, Denmark) and RadioEar DD45 headphones (RadioEar, Middelfart, Denmark). Voice cue discrimination data were collected with a custom-made interface (Fig. 2), implemented with MATLAB and using a portable touchscreen laptop (Yoga; Lenovo, Beijing, China). All children and adults with NH were tested with headphones (HD 380 Pro; Sennheiser, Wedemark, Germany), and children with hearing aids were tested with speakers (Z200; Logitech, Apples, Switzerland). The speakers were located behind the laptop and facing the participant at a distance of approximately 70 cm. Prior to data collection, stimuli were calibrated both with the test headphones and speakers in an anechoic chamber using a sound level meter (Svantek 979; Svantek Sp, Warsaw, Poland) and a KEMAR head and torso simulator (45BB KEMAR Head and Torso; G.R.A.S. Sound & Vibration A/S, Holte, Denmark). Hearing-aided children used their own bilateral hearing aids in their everyday/usual program and were instructed not to change their settings during the experiment.

H. Data analysis

We examined how hearing-aided children's sensitivity to F0 and VTL cues develops as a function of age compared to NH children, by analyzing the F0 and VTL JNDs and using a number of models to answer different research questions. All statistical analyses were performed in R (version 4.2.3; R Core Team, 2020).

First, we compared the JNDs between the hearing-aided and normal-hearing children. More specifically, this analysis specifically included, in addition to the group effect, also the developmental effects with age, both within the groups and

in comparison to each other. For this analysis, we applied generalized additive models (GAMs) specifically for the NH and hearing-aided children, using the `MGCV` (v.1.8.42), `ITSADUG` (v.2.4.1), and `GRATIA` (v.0.8.1) packages in R. With GAMs, we are able to model both linear and non-linear relationships between dependent and independent variables, which is particularly suitable to examine the effect of age. Furthermore, the JNDs were log-transformed to improve the normality of their distribution, as was described in previous studies (e.g., Nagels *et al.*, 2020). To examine the development of JNDs as a function of age for each group, we used the following model:

$$\log(\text{JND}) \sim \text{Group} + s(\text{Age}, \text{by} = \text{Group}).$$

The spline used for age was a thin-plate regression spline fitted per group (NH, hearing-aided), with the k -parameter set to 10, such that the model uses at most 9 basis functions to fit the data. In the model, the groups had different intercepts (which represents the constant difference across groups throughout ages), as well as different spline functions. Therefore, the groups were compared first by comparing their intercepts and then by estimating the spline of the difference between groups (including the intercepts). The 95% confidence interval of this difference spline was used to find the age range(s) where the groups differed significantly. Differences were considered significant at ages where the confidence interval of the difference did not include 0.

Second, we investigated the age of maturity in NH by characterizing the age effect throughout the school age range and early adulthood. For this purpose, we fitted a GAM to the JNDs of the NH child and adult participants. This model included a spline per voice cue. To evaluate the age at which development is complete, we estimated the derivatives of each spline, along with the 95% confidence interval. The maximum age at which the slope of the spline representing the JNDs as a function of age was no longer different from 0 is reported as the age of maturity for this cue's JNDs.

Third, we included an analysis for individual data of children with hearing aids. More specifically, we analyzed how the individual JNDs of the hearing-aided children compared to the JNDs of NH participants. We estimated the distribution of F0 and VTL JNDs of children and adults with NH, to observe where JNDs of children with hearing aids would fall within this distribution. Here, similar to the approach by Nagels *et al.* (2024), we used a quantile regression based on GAMs using the `QGAM` package (version 1.3.4) (Fasiolo *et al.*, 2021) in R. The fitting method in `QGAM` is non-parametric and hence does not have the assumption of normality. When compared to other traditional regression techniques, quantile regression as an extension of the linear regression model offers a more complete view of the relationships between variables by estimating the full distribution of JNDs, rather than just the mean, and highlighting various percentiles. Thus, we can model linear and nonlinear

relationships between response and predictors such as age in this study. Additionally, this kind of group-level and individual comparisons reduces the risk of type II errors (which can be attributed to a lack of power).

Last, we have explored potential effects of hearing thresholds (unaided or aided) on the JNDs measured from the children with hearing aids. This was done by comparing GAM fits to the JNDs from the hearing-aided group, where the PTA4 (based on mid-range frequencies of 500 to 4000 Hz, which largely overlaps with important speech frequencies and formant regions) was added as predictor. Based on previous literature (Flaherty *et al.*, 2021a), we also tested the low-frequency PTA (LFPTA; average of thresholds at 250 and 500 Hz) as a predictor. However, Flaherty *et al.* (2021b) used a range of F0s in their experiment that were relatively high—250.5 to 357.6 Hz—as their target voice was prepared to have a higher F0 than the reference average F0, 250 Hz. As a result, the range of F0s they used partially overlapped with the range of frequencies of LFPTA. Our F0 manipulations, in contrast, involved lowering the F0 from the original reference voice and therefore covered an F0 range between about 120 and 240 Hz, which did not overlap as much with the LFPTA frequencies. For this reason, we also introduced an extended low-frequency pure tone average (ELFPTA), defined as the average of thresholds at 125 and 250 Hz, to investigate as a predictor. ELFPTA was available in 35 of the 53 hearing-aided children.

Note that all fitting was performed using the restricted maximum likelihood (REML) method because it is considered unbiased (Snijders and Bosker, 2011). The only exception concerns the PTA predictor estimation presented above, where significance was evaluated using likelihood ratios to compare models that differ by their fixed effects. In this case, it is recommended to fit the model using the maximum likelihood (ML) method (Faraway, 2006; Snijders and Bosker, 2011).

III. RESULTS

A. Group comparison for age and voice cue sensitivity

The results of the GAM analysis for comparing hearing-aided and NH child groups are presented in Fig. 3, top and bottom panels, for F0 and VTL, respectively. With this GAM analysis, the effect of *age* on the JNDs was evaluated within each group (NH and hearing-aided), as well as the ages at which the groups differed from each other. Age had a significant effect on the F0 JNDs, for both the hearing-aided [$F(1,137)=19.2, P < 0.001$] and the NH [$F(1.48,137)=5.58, P < 0.01$] groups. This implies that in both groups, F0 JNDs developed as a function of age [Fig. 3(A)]. The F0 JNDs of the hearing-aided and NH children differed significantly from each other between the ages of 7.7 and 12.0 years, and there was no significant group difference after the age of 12.0 years.

The GAM analysis of the VTL JNDs showed a significant effect of age on the JNDs for the hearing-aided group

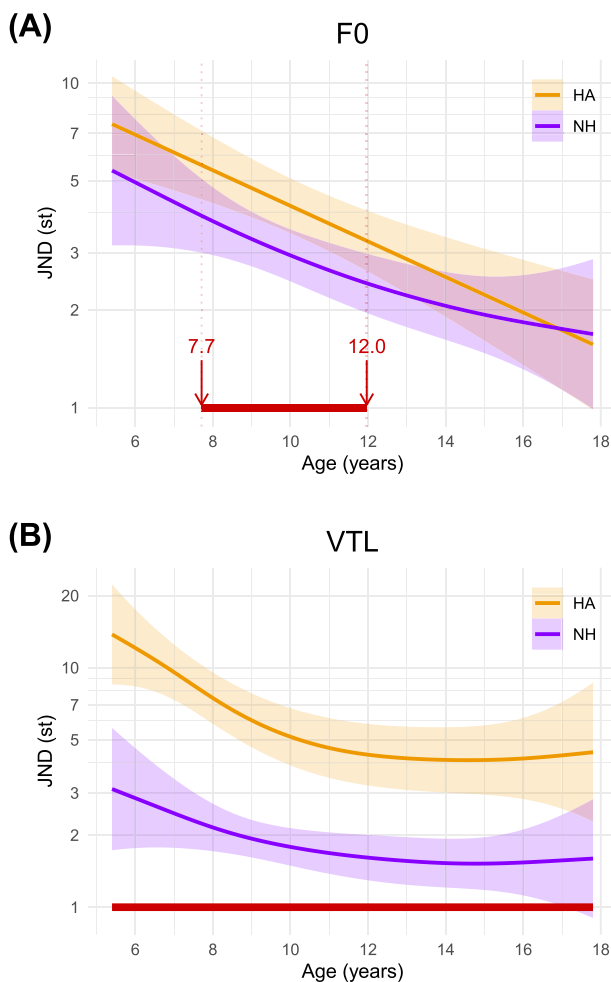


FIG. 3. (Color online) GAM analysis for the group comparison of the developmental patterns of just-noticeable differences (JNDs), shown in semitones (st) and as a function of age (years) for hearing-aided (HA) and normal-hearing (NH) children. F0 and VTL JNDs are shown in panels (A) and (B), respectively. The dark (purple) line represents the estimated JNDs of the NH children, and the light (orange) line represents the estimated JNDs of the HA children as a function of age. Shaded areas represent 95% confidence intervals. The thick (red) line on the x axis indicates the age range where the estimated differences in JNDs between the NH and HA groups significantly differ from zero, indicating a significant group difference. Note that the y axis is expressed in st, but is log-spaced to reflect the fact that the analysis was performed on the log-JNDs.

[$F(2.34,135)=6.78, P < 0.001$], but not for the NH group [$F(1.86,135)=2.03, P = 0.14$]. This implies that only in the hearing-aided group, but not in the NH group, VTL JNDs seemed to develop as a function of age [Fig. 3(B)]. The difference in VTL JNDs between the hearing-aided and NH children remained significant throughout the full age range, up to adulthood.

B. Age of maturity in NH

The age of maturity in NH was investigated by fitting a GAM to the JNDs of the NH child and adult participants (shown by small gray circles in Fig. 4). We used these data for full characterization of development of voice cue

sensitivity in normal hearing. For developmental trajectories in NH individuals, specifically focusing on the JND data from all participants with NH, a significant age effect was observed for both F0 [$F(2.08, 303)=21.4, P < 0.001$] and VTL [$F(1.88, 303)=3.41, P < 0.05$]. These trajectories can be illustrated by the median (50%) lines in Fig. 4.

Evaluating the slopes of these splines revealed that maturity for F0 JNDs was only reached at the age of about 24 years, whereas the age of maturity for VTL JNDs was found to be about 14 (with the upper confidence interval making only a brief incursion below zero between 10.5 and 14.1). Note that these ages should not be considered normative. Instead, they provide a rough indication of how much slower the development of F0 discrimination may be compared to VTL discrimination.

C. Individual data analysis

The quantile regressions of F0 and VTL JNDs over age are shown in Fig. 4 for NH child and adult participants. In this analysis, we estimated the distribution of JNDs of the NH participants based on their chronological age (gray area). The age of maturity was presented in the previous subsection; here, we only aimed to compare individual JND data from hearing-aided children to the estimated NH JND distribution. For this purpose, the JND measurements of children with hearing aids (colored diamonds) are superimposed with the JNDs of participants with NH (gray circles) and the corresponding estimated JND distribution (gray area). The color codes for the JNDs of hearing-aided children represent the audiometric thresholds of the hearing-aided children, separately presented for unaided [Fig. 4(A)] and aided [Fig. 4(B)] PTA4 values. Based on the estimates from the NH group, we made observations about how the JNDs of the hearing-aided children (indicated by shown with colored diamonds) are placed within these distributions. In comparing individual JNDs of hearing-aided children to the estimates from NH participants, we can visually observe that the F0 JNDs of hearing-aided children overlap to a large degree with JNDs of the NH children. Further, a developmental age effect is visually observed in both hearing-aided and NH children, in line with the GAM analyses reported above. In contrast, the VTL JNDs of hearing-aided children overlap less with that of NH children. VTL JNDs of hearing-aided children were almost all above the median JND values (higher sensitivity) of NH children.

To better visualize to what degree the hearing-aided group deviates from the NH distribution, we plotted the F0 and VTL JNDs of the hearing-aided children as quantiles of NH distribution (see Fig. 5). Visual inspection shows that there is more overlap of F0 JNDs than VTL JNDs of hearing-aided children with JNDs of NH children. For F0, 20 out of the 55 hearing-aided children have JNDs below the median (50th percentile) and only 8 hearing-aided children are above the 95th percentile, indicating a large overlap in JNDs between the two groups. For VTL, only 2 hearing-

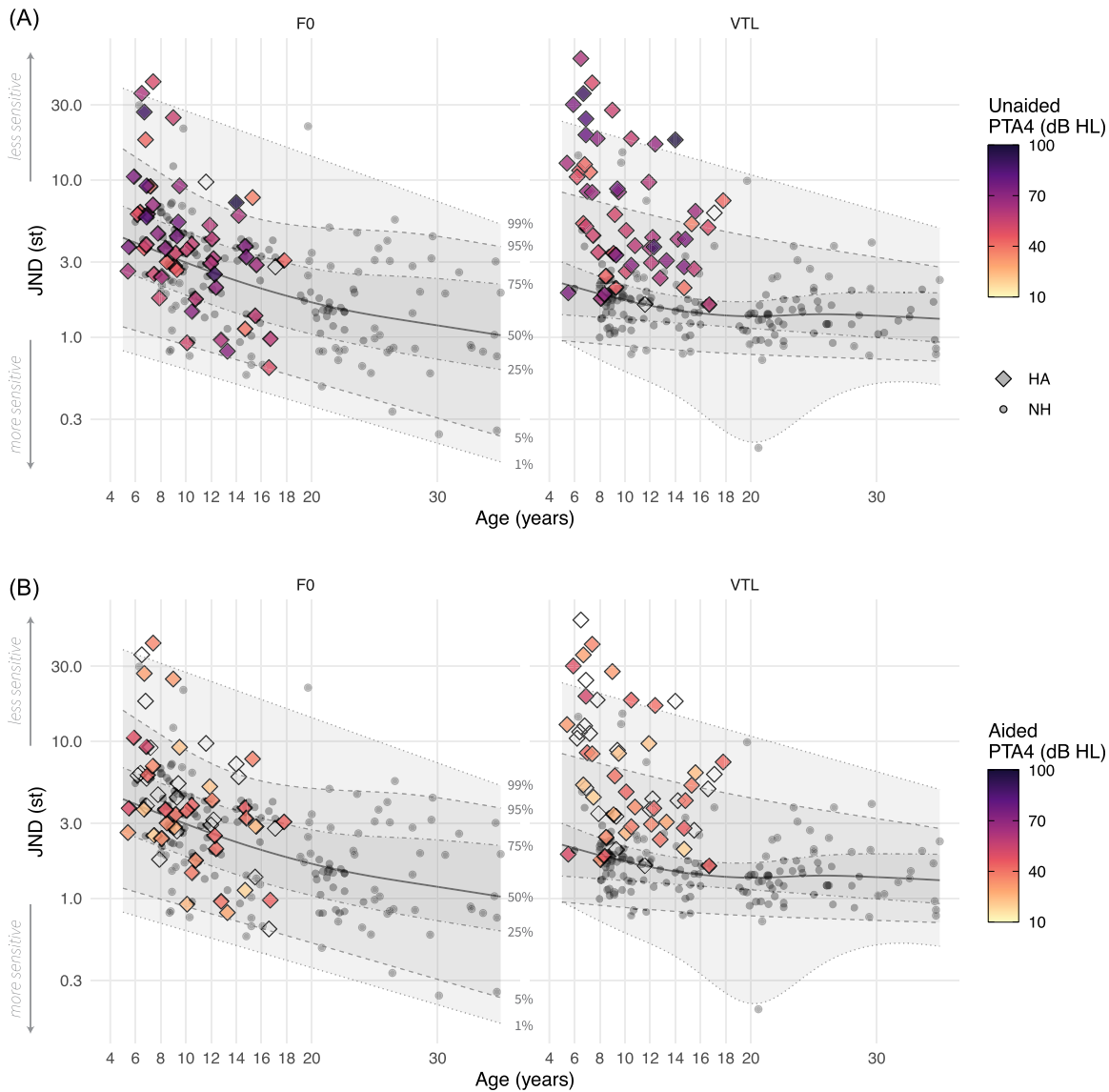


FIG. 4. (Color online) JNDs for F0 (left) and VTL (right) shown for children and adults with normal hearing (NH) (gray circles, $N = 154$) and children with hearing aids (HA) (colored and empty diamonds, $N = 55$). The solid lines represent the median (50th percentile), and the dashed and dotted lines and the shaded areas represent the 1st, 5th, 25th, 75th, 95th, and 99th percentiles, estimated based on the quantile regression analysis of NH children and adults. The color of the diamonds represents the pure-tone average hearing thresholds over 500, 1000, 2000, and 4000 Hz (PTA4) in dB HL. In panel (A), the colored diamonds represent the unaided PTA4 of HA children ($N = 53$), and the empty diamonds ($N = 2$) represent when the unaided PTA4 was not available. In panel (B), the colored diamonds represent the aided PTA4 of HA children for whom this information was available ($N = 35$), and the empty diamonds represent the remaining HA children ($N = 20$). Similar to Fig. 3, the y axis is expressed in st but is log-spaced to reflect the fact that the analysis was performed on the log-JNDs.

aided children have JNDs below the median and 24 hearing-aided children are above the 95th percentile, indicating a smaller overlap than observed with F0 JNDs and that most hearing-aided children show larger VTL JNDs than their NH peers.

D. Potential effects of hearing thresholds

A visual inspection of Figs. 4 and 5 indicates no clear gradient of color along the vertical axes, suggesting that there seems to be no consistent influence of either unaided

or aided PTA4s on either of the JNDs. This is confirmed by comparing GAM fits to the JNDs from the hearing-aided group, where the PTA4 was added as predictor. For F0 JNDs, neither unaided [$\chi^2(1) = 0.33$, $P = 0.42$] nor aided [$\chi^2(1) = 0.20$, $P = 0.52$] PTA4s had a significant effect. Similarly, for VTL JNDs, neither unaided [$\chi^2(1) = 1.49$, $P = 0.08$] nor aided [$\chi^2(1) = 0.04$, $P = 0.78$] PTA4s had a significant effect. Unaided LFPTA also had no significant effect on either F0 [$\chi^2(1) = 0.61$, $P = 0.27$] or VTL JNDs [$\chi^2(1) = 0.19$, $P = 0.54$]. However, the unaided ELFPTA, which better corresponds to the range of F0s tested in

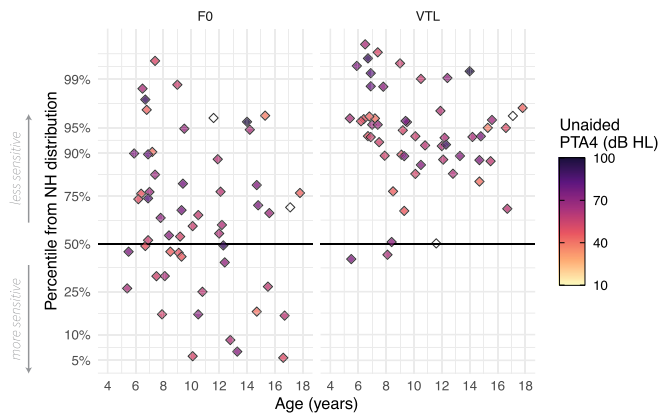


FIG. 5. (Color online) Individual JNDs of hearing-aided (HA) children ($N = 55$) plotted as quantiles of the distribution of data from normal-hearing (NH) children, for F0 (left panel) and VTL (right panel). The colored diamonds show the individual JNDs of HA children, with color indicating their unaided PTA4 [same coloring as Fig. 4(A)] and the diamonds with no color indicating JNDs of HA children with no PTA4 information.

this study, did contribute significantly to the F0 JNDs [$\chi^2(1) = 2.51, P < 0.05$], but not to the VTL JNDs [$\chi^2(1) = 1.15, P = 0.13$].

IV. DISCUSSION

The aim of this study was to provide a comprehensive overview of voice cue perception in a relatively large group of school-age children with hearing aids. The developmental effects were investigated by also taking into account age and including data from NH children and adults. More specifically, we have investigated voice cue perception via a discrimination task and by measuring JNDs of two principal voice cues, F0 and VTL, in school-aged children with hearing aids, as well as age-matched children and adults without hearing loss.

A. Group differences and developmental effects

Quantifying voice cue perception in a child with hearing aids would not be possible without the baseline developmental trajectories, since otherwise what effect comes from age-typical development and what effect from hearing status cannot be teased apart. In this study, we had aimed to cover a wide range of ages for inclusion to fully characterize developmental effects in school-age years. When the JNDs from the two children’s groups were compared, as a function of age to account for developmental effects, our results showed significant group differences over most of the age range. For F0, the JNDs of hearing-aided children were significantly larger than those of NH children below the age of 12. For VTL, the difference between the groups was significant across the entire age range from 5 to 18 years. Hence, overall data indicate a lower sensitivity to voice cue perception in hearing-aided children relative to their NH peers (Fig. 3), in line with previous similar research (Flaherty *et al.*, 2021a; Halliday *et al.*, 2019; Kirby *et al.*, 2015; Kirby *et al.*, 2019; Nagels *et al.*, 2020; Zaltz *et al.*, 2020), and this difference is age-dependent.

The differing developmental trajectories were also apparent in other analyses of data. When the JNDs were analyzed for age per group, the developmental effects differed between the groups and also for the two voice cues. In children with hearing aids, while overall voice cue sensitivity was lower than that of children with NH, there was a significant age effect on both F0 and VTL JNDs. In children with NH, there was a significant age effect only on F0 JNDs, but not on VTL JNDs. Development of F0 perception, or frequency discrimination in general, has been more commonly reported in NH children in previous studies (Banai, 2008; Buss *et al.*, 2017; Deroche *et al.*, 2012; Flaherty *et al.*, 2019; Jensen and Neff, 1993; Maxon and Hochberg, 1982), but VTL perception has been less investigated (Flaherty *et al.*, 2021b; Nagels *et al.*, 2020; Zaltz *et al.*, 2020). VTL perception relies on perception of formants (e.g., Ladefoged and Broadbent, 1957) and, hence, on spectral resolution. A number of studies with measures of spectral resolution reported a significant age effect (Jahn *et al.*, 2022; Kirby *et al.*, 2015; Kirby *et al.*, 2019; Moore *et al.*, 2011). On the other hand, perhaps VTL perception still relies on a broader mechanism than spectral resolution only, as some aspects of VTL cue use, such as for estimating a speaker’s size, were suggested to be an innate automatic process (e.g., Vestergaard *et al.*, 2009), in contrast to long developmental trajectories of spectral resolution.

The only two studies that investigated both F0 and VTL discrimination directly, together in one study and in designs similar to ours, are by Nagels *et al.* (2020), with Dutch children, and Zaltz *et al.* (2020), with Israeli children. Note that while Flaherty *et al.* (2021b) studied the effects of the voice cue difference for F0 and VTL for perception of speech in a two-talker masker, they did not report direct measures of F0 and VTL cue sensitivity. Nagels *et al.* reported that F0 JNDs of 12-year old children with normal hearing were still significantly different from JNDs of adults, whereas VTL JNDs were already at adult-like levels in 8-year old children. Nagels *et al.* (2020) had collected data in children until the age of 12 only. The results of the present study complement their findings, by adding data for the development of voice cue sensitivity from the age of 12 to adulthood. Zaltz *et al.* (2020) reported that 8- to 11-year old children showed voice cue sensitivity similar to adults for both F0 and VTL, differing from our and the Nagels *et al.* study findings. The differences between all three studies could be due to differences in design, as Banai (2008) has shown that the developmental trajectories can differ even in the same group of children, depending on the methods and tasks used. While our study and the study by Nagels *et al.* (2020) used CV triplets, Zaltz *et al.* (2020) used sentences. The effect of differing lexical content on voice cue discrimination was previously shown, with richer lexical content and longer stimuli like sentences generally leading to smaller JNDs (Koelewijn *et al.*, 2021; Koelewijn *et al.*, 2023; Meister *et al.*, 2016). While the studies by Nagels *et al.* (2020) and Zaltz *et al.* (2020) used stimuli produced by a single female talker, in our study, we used stimuli produced by three female talkers (due to the labeling

error previously explained). While the three speakers had similar voices and heights, this variation may still have contributed to relatively higher JNDs of the present study and further affected the observed developmental trajectories. On the other hand, the differences could also be due to differing languages, e.g., how well F0 or VTL-related acoustic cues are expressed in speech signals for a specific language or to what degree these cues may be important for speech communication in that language. Each of the three languages, Turkish, Dutch, and Hebrew, belongs to a different language family, i.e., Turkic (Ural-Altai in older classifications), Indo-European, and Afro-Asiatic, respectively, and the overlap and differences between the languages vary. There seems to be more overlap between Turkish and Dutch for perceptual similarity in phonetic and phonological content (for example, see Tables I and II in Bradlow *et al.*, 2010), and in some prosodic elements (McLeod and Goldstein, 2012), than between Turkish and Hebrew. This overlap may be the reason for the observation that both Dutch and Turkish children show a strong developmental trajectory for F0 perception. On the other hand, there seems to be more consensus between the three studies for VTL perception. Nagels *et al.* (2020) showed with Dutch children some VTL perception improvement until the age of 8 years. Zaltz *et al.* (2020) showed with Hebrew children comparable JNDs at 8 years to those of adults. Our results from the present study indicated no age effect, meaning that by the youngest group (around 5 to 6 years) already the VTL JNDs were comparable to that of adults. One last data analysis for development was conducted using combined data from NH children and adults. The GAM quantile regression in Fig. 4 and the spline slope analysis both suggest that F0 JNDs might keep improving with age until the age of 24 years, whereas for VTL JNDs maturation was implied at the age of 14 years. This finding is also compatible with the conclusions of Nagels *et al.* (2020), but it is worth noting that since the maximum age in our dataset was 35 years, there is a rather large uncertainty about the exact slope of the JNDs as a function of age. Data collection from participants from more advanced ages is necessary to better appraise the precise age of maturity for voice cue sensitivity.

In short, despite the group differences, and the lack of developmental effect for VTL sensitivity within the group of NH children, we found that both F0 and VTL sensitivity improved with age in the hearing-aided group. While the group difference for VTL sensitivity remained across all ages, F0 sensitivity development seemed to be catching up with age-typical development after the age of 12 years. Previously, it was shown that children who were prelingually deafened and implanted have smaller JNDs (better sensitivity) for voice cue perception compared to adults who were postlingually deafened and implanted (Nagels *et al.*, 2024). Early-implanted children develop hearing via the cochlear implant and may be taking advantage of an effective learning period for perception of degraded voice cues due to early exposure and plasticity. In contrast, late-deafened and -implanted adults will have developed hearing

via acoustic input, and following, they have to re-adapt to degraded cues via the implant. Perhaps it is more difficult to unlearn the patterns from acoustic hearing and replace them with patterns of electric hearing at a later age, without the plasticity advantage. Supporting this idea, Tomblin *et al.* (2015) state that the sensitive learning period for language development seems to stay open for an extended period of time in children, during which hearing loss may slow down the development and hearing aid may speed it up. Thomas *et al.* (2009) investigated developmental trajectories in general for language and cognitive impairments in children. The authors reported these trajectories to differ from each other for different disorders, yet, in many cases, development seems to take place. Walker *et al.* (2019), in a longitudinal study, observed that, while speech recognition development in children with hearing aids was delayed compared to that in children with NH, the growth trajectories were parallel to each other between the two groups. Hence, literature suggests that children in general could potentially adapt and learn to make effective use of the voice cues that are altered due to hearing loss but likely somewhat compensated for by the hearing aids. Hence, the possibility exists that these children eventually catch up with age-typical development with further hearing aid use.

B. Individual differences and hearing related factors

The differences in perception of F0 and VTL were also apparent in comparisons of individual data of hearing-aided children to the distribution of data of NH children. The individual JNDs from the two children groups present considerable overlap, but to a different degree for F0 and VTL. This degree of overlap is due to large variability not only in the hearing-aided group, but also in the NH group. For F0 JNDs, Fig. 4 indicated that a large proportion of hearing-aided children were able to perform this task with the same level of proficiency as NH children. Indeed, nearly half (25 out of 55 [45%]) of the hearing-aided JNDs fell between the 25th and 75th percentiles of the NH distribution. Therefore, despite the significant group difference, we should not conclude that all children with hearing aids experience difficulties in F0 voice cue perception. For VTL JNDs, while hearing-aided children also showed a large variability, almost all of them (49 out of 55 [89%]) had discrimination thresholds that were beyond the 75th percentile of the age-matched NH group, and two-thirds of them (37 out of 55 [67%]) had discrimination thresholds beyond the 90th percentile of the NH distribution. Hence, overall, in our data, hearing-aided children's JNDs deviated from the NH children distribution more for VTL discrimination than for F0 discrimination.

An interesting observation is on the JNDs of children with profound hearing loss (PTA₄ > 80 dB HL or higher). As a result of our relaxed inclusion, we had four children with profound hearing loss. These children were 14.0, 6.9, 6.7, and 12.3 years old and had PTA₄s of 97.5, 83.8, 90.0, and 90.0 dB HL, respectively. These high PTA₄s imply that these

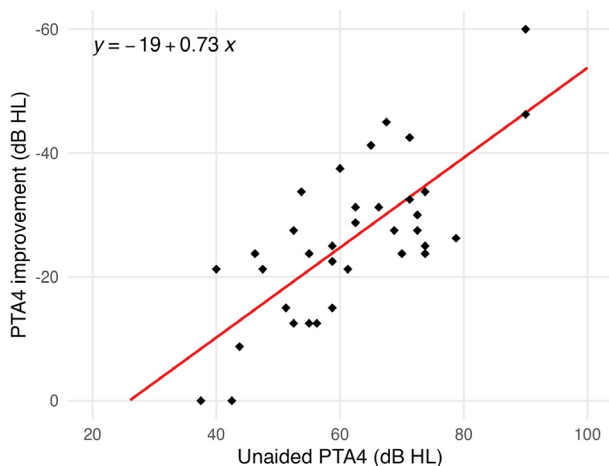


FIG. 6. (Color online) PTA4 improvement (aided PTA4 minus unaided PTA4) shown as a function of unaided PTA4 for $N = 35$ hearing-aided children. The (red) solid line represents the correlation between unaided PTA4 and PTA4 improvement.

children could be candidates for cochlear implants. On the other hand, they are active users of their hearing aids, with the 14.0-year old using their hearing aid more than 13.0h/d and the 6.9-year old participant using more than 7.0h/day. Figure 6 shows the improvement in PTA4 for the children where both aided and unaided PTA4s were available.

These data indicate that the two children with PTA4 = 90 dB HL have substantial improvement in their aided thresholds with their hearing aids. While the JNDs of these four children were variable (F0, 7.3 st, and VTL, 18.0 st; F0, 5.8 st, and VTL, 24.5 st; F0, 27.0 st, and VTL, 35.5 st; and F0, 2.5 st, and VTL, 3.7 st, respectively), their data points did not show as outliers in comparison to the overall data (Fig. 4). From these four children with profound hearing loss, for the two younger ones, 6.7 and 6.9 years, their age-matched NH peers also had large JNDs. Hence, for this age group, there is still a possibility for voice cue perception to further improve with hearing aid use. For the two older children, while one produced high JNDs, the other one had very low JNDs, to the degree that the F0 JND of 2.8 st was on the median value of NH distribution for their age bracket. These results combined show that, even with profound hearing loss, these children were able to do the voice discrimination test and produce meaningful JND values that were comparable to expected distributions from their age bracket. Hence, even in profound hearing loss, active use of hearing aids seems to be helping with voice cue perception.

In an effort to understand the large variability in voice cue perception in the entire group of hearing-aided children, we investigated the potential factors that may explain the individual differences observed. Some of the factors that could be expected to have an influence on voice cue perception demonstrated little variation within our test population and are thus unlikely to explain much of the individual differences we observed. First, all hearing-aided children were healthy, in good audiological care, and had been using their

hearing aids for 6 months or longer. Second, there was also some homogeneity in a number of factors related to the hearing aids. All hearing-aided children used pediatric digital hearing aids (mostly Sky [$N = 38$], then Naida [$N = 10$], Bolero [$N = 4$], then Audeo [$N = 3$]) by the same manufacturer (Phonak). Most hearing aids were BTE ($N = 52$), except for a few receiver-in-the-ear versions ($N = 3$). All earmolds had been replaced, as needed, following standard audiological procedures, and they were further checked at the time of testing. The hearing aids had been fitted based on the prescriptive algorithms as suggested by the fitting program and fine-tuned by audiologists as needed (mostly DSL-V5 [$N = 50$] and NAL-NL2 [$N = 1$], AdaptivePhonak [$N = 1$] and Unknown [$N = 3$]). Third, data logging from the devices indicated relatively long daily hearing aid use, with a group average of 12.0h/day (with most children using their hearing aids 7.0h or longer: $N = 26$ out of 28 children with these data available). Finally, some demographic factors related to education also showed little variability across the hearing-aided children. All children received a similar form of education in mainstream state schools and received comparable hours of music training at school.

On the other hand, beside these similarities within the group of hearing-aided children, as listed above, our participants did show large variations in other aspects. Due to inclusion of all bilateral hearing aid user children with no strict exclusion for hearing status, we did expect such variations, and some relevant potential factors are discussed below.

1. Unaided thresholds

One of the factors we investigated for individual variability in JNDs in children with hearing aids was the PTA4 of unaided thresholds, as a proxy for the degree of hearing loss. In this study, to capture a good overview of both age and hearing status, our inclusion on both factors was minimally restrictive. As long as a child could do the test and was a user of bilateral hearing aids for 6 months or longer without any additional health problems, they could participate in our experiment. This resulted in a wide range of ages, only limiting the youngest participant age to around 5.4 years, and also a wide range of hearing loss degrees, ranging from moderate to profound (unaided PTA4 range = 37.5–97.5 dB HL). As discussed in Sec. I, voice cue perception could be affected by both the effects of elevated thresholds, as well as the suprathreshold effects related to the degree of hearing loss, such as spectral resolution being compromised for moderate and severe hearing losses (Baker and Rosen, 2002; Başkent, 2006; Nelson, 1991; Rosen *et al.*, 1990). Our data showed different patterns for F0 and VTL discrimination thresholds, where VTL JNDs of hearing-aided children generally deviated more from those of NH children than F0 JNDs did. This finding is in line with previous studies that implied differing reliance on and sensitivity to temporal and spectral cues in general in individuals with hearing loss (e.g., Souza *et al.*, 2015). Further,

literature also suggests that access to very limited bandwidth low-frequency acoustic cues may be sufficient for F0 perception (Arehart, 1994; Başkent *et al.*, 2018; Gaudrain and Başkent, 2015; Straatman *et al.*, 2010). Hence, individuals with hearing loss could achieve F0 discrimination as long as they have reasonable hearing thresholds at low frequencies. VTL perception is on the other hand closely related to the perception of formants, which is assumed to rely on spectral resolution of the broad bandwidth of the speech signal and therefore could be more likely to be affected by elevated hearing thresholds at a wider range of frequencies. The deviating patterns of F0 and VTL perception we have observed could therefore be related to the varying degrees and configurations of hearing loss of the children and the accompanying potential suprathreshold deficiencies.

To explore the effects of the unaided thresholds on the F0 and VTL JNDs, we have run data analyses for the correlations of JNDs with PTA4s (based on mid-range speech frequencies, between 500 and 4000 Hz), LFPTA [e.g., based on Flaherty *et al.* (2021a), and low frequencies, 250 and 500 Hz], and ELFPTA (125 and 250 Hz, overlapping with the average F0 ranges of the talkers that produced the stimuli of the present study, 201–217 Hz). From all the correlations, only ELFPTA showed a significant correlation with F0 JNDs, indicating that the hearing loss at the region needed for average F0 perception could be an important factor, in line with the findings of Flaherty *et al.* (2021b). For F0 perception, perhaps this is not as surprising. PTA4 calculations are based on the frequencies that seem to be most important for speech intelligibility in general (e.g., SII) (ANSI, 1997); however, F0 perception likely depends on other mechanisms, such as resolving low order harmonics (e.g., Moore *et al.*, 1985) coded in low frequencies, as suggested above. For VTL perception, there was no correlation of the JNDs with any of the unaided hearing thresholds. This is perhaps slightly surprising, as VTL perception relies on spectral resolution, and the formants in Turkish, needed for VTL perception, partially, but not entirely, coincide with the range of the frequencies of PTA4 (e.g., Korkmaz and Boyacı, 2018).

The differences observed in F0 and VTL JNDs in relation to hearing thresholds may imply the differences in perceptual and cognitive mechanisms for F0 and VTL processing. Nagels *et al.* (2020) interpreted their results on differing developmental trajectories for F0 and VTL perception within NH children as such that VTL perception may become adult-like earlier because it is more closely linked with linguistic content, i.e., due to the use of formants which also define vowels (Ladefoged and Broadbent, 1957). In contrast, average F0 plays no such role, other than the F0 intonations and prosody (e.g., Everhardt *et al.*, 2020). This idea further was supported by recent studies that showed differential effects of the changing lexical content of the stimuli on F0 and VTL perception, indicating potentially differing involvement from cognitive processes (Koelewijn *et al.*, 2021, Koelewijn *et al.*, 2023; Meister *et al.*, 2016). The present results suggest that F0 perception seems to rely

more on detection of relevant low-frequency acoustic cues, and therefore, hearing thresholds at the relevant low-frequency region seem to play an important role. On the other hand, VTL perception perhaps relies more on the availability of the information above thresholds, more specifically, the energy distribution of formants, and their correct interpretation, also using language knowledge. Hence, here, not hearing thresholds, but perhaps the audibility above thresholds and the potential suprathreshold distortions that can affect the VTL cues play a larger role. Future studies could investigate these aspects by including measures for audibility and spectral resolution to directly investigate the relation between these and VTL perception.

2. Aided thresholds and hearing aid settings

Another factor we had investigated was aided thresholds. The aided audiograms available from $N = 35$ children showed a wide range in aided thresholds (Fig. 1; aided PTA4 range = 18.8–52.0 dB HL, average = 35.8 dB HL). The difference between the aided and unaided PTA4 for these $N = 35$ children is shown in Fig. 6. Two children with low unaided PTA4s (37.5 and 42.5 dB HL) had no measurable PTA4 improvement; however, the other children ($N = 33$) gained 8.8 to 60.0 dB HL, with an average of 27.6 dB HL, with especially the children with the most severe hearing loss showing the largest PTA4 improvement. While there is a range in the PTA4 improvement as a function of hearing aid amplification, this range was mostly a function of the unaided PTA4 (for all $N = 35$, Pearson correlation coefficient: $r = 0.74$, $P < 0.001$). Hence, while hearing aid seems to have helped with reducing hearing thresholds for most of the children, we observed no significant effect of aided thresholds on voice cue sensitivity for both F0 and VTL.

While aided thresholds would inform us how well soft sounds could be detected, audibility is more related to the amount of sound or speech energy that falls above aided thresholds. As explained before, it was not possible to include a verification of audibility, for example, using the 65 dB SII real ear measures, as was done in some previous studies (e.g., Kirby *et al.*, 2015; Flaherty *et al.*, 2021a). While such audibility was shown to be crucial for speech intelligibility (e.g., McCreery *et al.*, 2020; McCreery and Stelmachowicz, 2011; Scollie, 2008; Stiles *et al.*, 2012), it could be that a simple detection via lowered hearing thresholds could be sufficient for voice cue discrimination, as explained above, and an audibility measure may be less relevant. However, neither aided thresholds of the present study nor aided SII measures of the previous studies showed systematic correlations (e.g., Flaherty *et al.*, 2021a; Kirby *et al.*, 2015; Kirby *et al.*, 2019).

Without the verification of hearing aid fitting, it is difficult to further determine what amplification and audibility related factors could have contributed to the large variability in JNDs in hearing-aided children. In terms of audiological care, all children were fitted with hearing aids by trained

audiologists during regular visits and according to the prescriptive algorithms as was suggested by the fitting software (Marriage *et al.*, 2018; Scollie *et al.*, 2005). On the other hand, during the test sessions, using the Phonak target software, we could only verify that (i) the DSL prescription was used, (ii) the target levels for fitting as recommended by the fitting software were mostly achieved, and (iii) hearing aids were being used daily, as indicated by data logging. The literature suggests that, even when target prescription gain settings are used, there are inherent deviations in measured hearing aid gain benefits, especially for children with moderately severe to profound hearing loss (Folkeard *et al.*, 2020; McCreery *et al.*, 2013; Quar *et al.*, 2013). In addition, during the hearing aid fitting session, audiologists may have to make choices, for example, to accommodate for amplification tolerance, where they may start a child from a lower gain setting to encourage hearing aid use and acclimatization (e.g., Glista *et al.*, 2012). Finally, for moderate to profound hearing losses, despite the use of power hearing aids, the gain or the bandwidth provided by the hearing aid may not be sufficient to reach the prescribed gain (e.g., McCreery *et al.*, 2013). This could be the case for some of our child participants, although a number of them with profound loss still produced low JNDs. Given that patient ratings of overall communication ability and overall satisfaction with hearing aids did not seem to correlate with improved audibility (shown by using the Articulation Index by Souza *et al.*, 2000), the overall effects from hearing aid amplification seem to be determined by many factors combined. Hence, both audibility and also all of these factors combined could be contributing to a large variability in the degree of improvement of the audiometric thresholds after fitting and how well the children could differentiate the voice cues with their hearing aids.

We have also investigated potential effects from hearing aid features in children for whom the fitting report was available ($N=30$). Phonak's adaptive sound classification system (e.g., SoundFlow, AutoSense) was "on" for all children (default setting). Different noise canceling features unique to the manufacturer, such as NoiseBlock, WhistleBlock, etc., were all individually set or inactivated across children. Further, for 21 of these 30 children, SoundRecover, the frequency compression mode, was activated. Such features could provide listening comfort in dealing with the wide range of sounds in daily life, and frequency-compression algorithms could improve perception of high frequency sounds (for example, in perception of consonants, e.g., Hopkins *et al.*, 2014), sometimes with no benefit visible in audiometric thresholds (for a review, see McCreery *et al.*, 2012). Wide dynamic range compression (WDRC) was "on" for all $N=30$ children. While this feature compensates for reduced dynamic range and increases audibility (e.g., Souza and Bishop, 1999), it also inevitably has to alter the acoustic signal. Dynamic range compression is applied using specific attack and release times that can affect the amplitude envelope of the signal (Corey and Singer, 2021; Kates, 2010; Souza, 2002). The reduction in

amplitude contrasts may alter the formants, which was shown to affect vowel identification by listeners with mild to moderately severe hearing loss (Bor *et al.*, 2008). Since formants are also related to perception of VTL, this could also have had an effect on the VTL JNDs of the present study. It is not yet known how the potentially beneficial effects of amplitude compression combined with effects of such envelope alterations could influence overall voice cue perception.

3. Cumulative effects from auditory and linguistic experience

The information we have from the hearing-aided children on their unaided and aided thresholds, hearing-aid settings, and hearing-aid use are all based on measurements made at the time of testing or right before testing. It is possible that the participants of the present study vary in their accumulated auditory experience, which could affect the development of voice perception in a way similar to the development of speech and language, shown even for mild hearing losses (Bess, 1985; Moore *et al.*, 2020). Data logging readings indicate consistent hearing aid use within the period of up to 6 months prior to the time of testing, however, literature indicates that younger children do not use their hearing aids as consistently as school-age children (Nailand *et al.*, 2022; Persson *et al.*, 2020; Walker *et al.*, 2013). Parents were not explicitly asked about their child's hearing aid use over a longer period of time or during different times or in different environments, and we could not rule out potential effects from the early years of hearing aid use.

Many children in our study had a high chance of receiving their hearing aids at a relatively early stage of their lives, due to the neonatal screening programs. The neonatal hearing screening program in Turkey was implemented in the early 2000s and became a nationwide standard screening program in 2008 (Kemaloğlu *et al.*, 2016), even though regional differences are also observed in how effectively the screening is applied (Konukseven *et al.*, 2017). This early intervention is crucial for optimal speech and language development (Singer *et al.*, 2010; Yoshinaga-Itano *et al.*, 1998), as hearing loss could potentially delay speech and language development, even in cases of mild hearing loss or without adequate amplification (Delage and Tuller, 2007; Tomblin *et al.*, 2015; Walker *et al.*, 2015). One other factor that could also affect overall language development is the possible effect of maternity education level. We had not controlled for this factor, but retrospectively, we observed that the maternal education level differed between the groups of children with normal hearing and children with hearing aids, likely due to differing recruitment of the two groups. Maternal education level was previously mentioned as an overall speech language development risk factor (Halliday *et al.*, 2017).

On language development of the child participants of our study, we did not have access to clinical speech audiometry scores or any other standard measure of language

comprehension or expression via the medical records that were made available to us. The long testing duration for the experimental conditions made us have to give priority to the experimental data, and for practical reasons, we only had the chance to rule out speech developmental delays, dyslexia, or any speech production issues by asking the parents. While parents did not indicate any such problems, there could still be variations in language development within the participant population. In general, voice and lexical cues seem to be closely related to each other (Kreitewolf *et al.*, 2017; Nygaard, 2008; Saksida *et al.*, 2021; Van Berkum *et al.*, 2008). VTL influences the resonance characteristics of the vocal tract, which affects not only the perceived size of the speaker, but also the quality of vowel sounds, due to formant shifts, and hence, also overall speech intelligibility. Additionally, F0 is associated with the perceived voice pitch of speech, and variations in F0 can convey linguistic and emotional information. From this, one can deduce that perception of F0 and VTL and speech/language in general could be related. Evidence for such a connection is indicated by studies that showed F0 and VTL perception can change when linguistic content of the speech materials is altered (Koelewijn *et al.*, 2021; Koelewijn *et al.*, 2023; Meister *et al.*, 2016; Zaltz, 2023). In children, a connection between neural circuits for perceiving mother's voice and social communication skills (Abrams *et al.*, 2016) or a connection between the voice quality of a speaker, such as dysphonic voice, and language comprehension in children (Lyberg-Åhlander *et al.*, 2015) were shown. However, a potential connection of voice cue perception with language development *per se* seems less clear. Hence, whether there is variation in language development within the participants and whether this variation had affected their F0 and VTL JNDs (or *vice versa*) could not yet be addressed within this study.

In summary, in our study, all children attended mainstream schools, suggesting that despite the relatively high degrees of hearing loss hearing aid compensation provided good functionality for these children, and parental questionnaires did not indicate any additional difficulties. Hence, while our results imply that factors other than aided thresholds could play a role in voice perception development, we cannot confirm with the present data if these factors come from previous auditory and linguistic experience and how closely they may relate to speech and language development.

C. Implications for future studies and clinical practice

Within this group of children, some with substantial hearing loss, all children were able to do the voice cue perception test. The discrimination thresholds of hearing-aided children considerably overlapped with those of NH children. Further, the voice cue discrimination of the children with hearing aids showed a significant age effect, hence, even if delayed, perhaps a development and catching up with age-typical levels is possible. These results are promising, as they indicate that even though hearing aids

are developed predominantly for speech perception, they seem to also support voice cue perception. The hearing aids of the participants were not checked for fitting quality; thus, perhaps the results would become even better should there be a possibility to verify and perhaps further improve, where needed, hearing aid fitting for all children in future studies.

The study used a method of voice cue discrimination that was developed specifically to be able to identify the limits and extent of voice cue perception using auditory cues only. The paradigm is mostly based on earlier studies, to be able to compare the voice cue sensitivity to previous results with various populations (Başkent *et al.*, 2018; El Boghdady *et al.*, 2019; Gaudrain and Başkent, 2018; Nagels *et al.*, 2020; Nogueira *et al.*, 2021). Since the method focuses on the perception of an isolated voice cue, F0 or VTL, and since these seem to involve differing perceptual mechanisms (Nagels *et al.*, 2020), any potential sources for limitations in voice perception can be investigated in a systematic manner. While using speech samples such as syllables as stimuli brings us one step closer to real-life voice perception, for example, compared to using harmonic complexes (Arehart, 1994; Deroche *et al.*, 2014; Deroche *et al.*, 2016), in real life, children's perception of voices of talkers may still differ than what we observe with the perception of an isolated voice cue. In daily life, children could make use of other talker-related cues in addition to F0 and VTL (Abercrombie, 1967), take advantage of the knowledge of a familiar talker (Souza *et al.*, 2013), and also supplement their auditory perception with visual cues related to a speaker (Mathias and von Kriegstein, 2014). Hence, the abilities and limitations of voice cue perception in real life may differ from what is shown in this study and can only be shown comprehensively with follow-up studies that will use a range of methods that involve variations in stimuli.

Given that aided thresholds did not seem to directly influence hearing-aided children's discrimination thresholds, other factors should be considered in future studies through more systematic use of demographic data. Rather than a single factor, voice cue perception seems to be affected by a combined effect of many factors. Such factors can include etiology of hearing loss, early developmental effects, the quality and quantity of acoustic input in daily life, the duration of previous auditory deprivation, proper audiological intervention-follow up, consistency of hearing aid use, and the quality and quantity of linguistic interactions (Dirks *et al.*, 2020; Litovsky, 2015; McCreery and Walker, 2022; Persson *et al.*, 2020; Tomblin *et al.*, 2015; Walker *et al.*, 2015). To gain a comprehensive overview, additional measures would be needed, and consequently, a much larger population would have to be investigated in order to identify the relevant factors. Nevertheless, this study supports the idea that hearing aids could help with voice perception and good audiological care could give children the best chance to further develop voice perception in later years.

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DATA AVAILABILITY

The data presented in this study are available in DataverseNL at <https://doi.org/10.34894/8M9QJD>. The CV syllables are available at <https://doi.org/10.5281/zenodo.10403318>.

¹Link for the WHO World Hearing Report: <https://apps.who.int/iris/handle/10665/339913>.

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