Hearing Research 406 (2021) 108230

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Extended high-frequency hearing and head orientation cues benefit children during speech-in-speech recognition

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ARTICLE INFO

Article history:
Received 22 December 2020
Revised 3 March 2021
Accepted 18 March 2021
Available online 8 April 2021

Keywords:
Speech-in-speech perception
Extended high frequency hearing
Human development
Head orientation
Informational masking

ABSTRACT

While the audible frequency range for humans spans approximately 20 Hz to 20 kHz, children display enhanced sensitivity relative to adults when detecting extended high frequencies (frequencies above 8 kHz; EHFs), as indicated by better pure tone thresholds. The impact that this increased hearing sensitivity to EHFs may have on children's speech recognition has not been established. One context in which EHF hearing may be particularly important for children is when recognizing speech in the presence of competing talkers. In the present study, we examined the extent to which school-age children (ages 5-17 years) with normal hearing were able to benefit from EHF cues when recognizing sentences in a two-talker speech masker. Two filtering conditions were tested: all stimuli were either full band or were low-pass filtered at 8 kHz to remove EHFs. Given that EHF energy emission in speech is highly dependent on head orientation of the talker (i.e., radiation becomes more directional with increasing frequency), two masker head angle conditions were tested: both co-located maskers were facing 45°, or both were facing 60° relative to the listener. The results demonstrated that regardless of age, children performed better when EHFs were present. In addition, a small change in masker head orientation also impacted performance, with better recognition at 60° compared to 45°. These findings suggest that EHF energy in the speech signal above 8 kHz is beneficial for children in complex listening situations. The magnitude of benefit from EHF cues and talker head orientation cues did not differ between children and adults. Therefore, while EHFs were beneficial for children as young as 5 years of age, children's generally better EHF hearing relative to adults did not provide any additional benefit.

1. Introduction

Young, healthy humans are able to hear pure tones at frequencies up to approximately 20 kHz. Extended high-frequency (EHF) hearing (>8 kHz) is better for children, with typical age-related progressive loss of the highest frequencies beginning as early as late adolescence (Green et al., 1987; Rodriguez Valiente et al., 2014; Schechter et al., 1986; Stelmachowicz et al., 1989; Trehub et al., 1988). This auditory sensitivity to EHFs is generally measured using pure tone audiometry, but the specific contribution that this sensitivity has on speech understanding has only recently begun to be explored. Although the traditional view has been that EHF hearing holds little utility for speech perception, in part due to the speech perception methods used historically (Monson et al., 2014b), recent evidence contradicts this view (Hunter et al., 2020). Specifically, it has been demonstrated that EHF hearing for adults with normal hearing contributes to speech localization (Best et al., 2005), judgments of speech and voice quality (Monson et al., 2014a; Moore and Tan, 2003), discrimination of a talker's head orientation (Monson et al., 2019), and speech recognition in noise (Monson et al., 2019; Motlagh Zadeh et al., 2019; Trine and Monson, 2020). Thus, EHF hearing supports the detection and perception of speech, which may explain, in part, why some studies have reported that elevated EHF pure tone thresholds in otherwise normal-hearing adults show a relationship with poorer speech recognition in noise performance (Badri et al., 2011; Corbin et al., 2019; Motlagh Zadeh et al., 2019; Yeend et al., 2019).

Studies of EHF hearing in children are sparse and are generally focused on pure tone thresholds in quiet (Schechter et al., 1986; Schneider et al., 1980; Trehub et al., 1988; Trehub et al., 1989). For example, it has been shown that premature loss of EHF hearing is often a consequence of pediatric otitis media treated with pressure equalization tube surgery (Hunter et al., 1996). Premature EHF loss is also a marker for ototoxicity in children (e.g., from

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Abbreviations: EHF, extended high frequency.

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https://doi.org/10.1016/j.heares.2021.108230
0378-5955/

aminoglycoside administration for cystic fibrosis) and may be related to speech perception deficits (Hunter et al., 2020). Direct demonstrations of the utility of EHFs for speech perception for children are lacking, however some have shown that lower frequency bands that include some EHFs contribute to speech perception. Stelmachowicz et al. (2007) showed that access to the frequency band between 5 and 10 kHz improved fricative recognition in noise for children (ages 7-14 years) with and without hearing loss. Pittman (2008) showed that novel-word learning rates improved for 8- to 10-year-old children with and without hearing loss when they were given access to the frequency band between 4 and 9 kHz. McCreery and Stelmachowicz (2011, 2013) demonstrated that nonword repetition in noise was improved with access to the 8-kHz octave band (5.7 – 11.3 kHz) for children with normal hearing. Interestingly, McCreery and Stelmachowicz (2011) also reported that limiting high-frequency bandwidth resulted in a similar decrement in non-word recognition for both children and adults. Because the frequency bands tested in these studies included lower frequencies, whether EHFs *per se* contribute to speech perception for children remains an open question. The fact that children have enhanced EHF hearing relative to adults raises the possibility that children derive greater benefit from EHFs for speech perception than do adults.

One context in which EHF hearing may be particularly important for children is in complex listening situations, such as when listening to speech in a multitalker environment. It is well established that children have greater difficulty than adults when recognizing speech in noisy environments, especially when the background is composed of competing talkers rather than steady noise (Hall et al., 2002; Leibold and Buss, 2013). When recognizing speech in the presence of one or more competing talkers, children require a more advantageous signal-to-noise ratio (SNR) to achieve the same level of performance as adults until they reach their teenage years (Buss et al., 2017; Corbin et al., 2016; Flaherty et al., 2019; Leibold and Buss, 2013; Leibold et al., 2016). This prolonged developmental trajectory for speech-in-speech recognition is thought to be due, in part, to children's immature sound segregation as well as limitations in the ability to use spectrotemporally sparse cues when recognizing speech (Buss et al., 2017; Buss et al., 2019).

When there are two or more people talking at the same time, the listener needs to perceptually isolate the target speech from the competing masker and selectively attend to only those phonemic cues that are associated with the target. This process can be facilitated by acoustic differences that lead to increased perceptual dissimilarity between target and masker speech. Differences such as talker sex (Leibold et al., 2018; Wightman and Kistler, 2005), language (Calandruccio et al., 2016), speaking style (Baker et al., 2014), voice fundamental frequency (Darwin et al., 2003; Flaherty et al., 2019; Flaherty et al., 2020), talker head orientation (Monson et al., 2019; Strelcyk et al., 2014), and relative spatial location (Johnstone and Litovsky, 2006; Litovsky, 2005) can improve speech-in-speech recognition for most listeners, but children do not always take advantage of these differences to the same degree as adults. For example, when there is a difference in fundamental frequency (F0) between competing talkers, younger children's speech recognition improves to a lesser degree than older children and adults. In fact, children under 7 years of age show little to no benefit when there is a 9-semitone difference between target words and competing two-talker speech, despite a robust improvement in speech recognition thresholds (SRTs) for older children and adults (Flaherty et al., 2019). This suggests that the ability to use F0 in multitalker environments follows a prolonged developmental trajectory, requiring years of neural maturation and/or experience with language to fully mature.

In contrast, when the target and masker speech are spatially separated, children as young as 3 years of age often show adult-like improvements in speech recognition relative to when the target and maskers are co-located (Garadat and Litovsky, 2007; Johnstone and Litovsky, 2006; Litovsky, 2005). In these studies, the target speech was presented from a single loudspeaker directly in front (0° azimuth) of the listeners, while the masker speech was presented either from a second loudspeaker to the right (90° azimuth) of the listener or was presented from the same single loudspeaker as the target, directly in front of the listener (0° azimuth). Although children still required a higher SNR than adults overall, 3-year-old children showed a similar benefit of spatial separation as 5-year-olds (Garadat and Litovsky, 2007), and 5- to 7-year-old children benefitted to a similar degree as adults (Litovsky, 2005). While there are some exceptions (e.g., Yuen and Yuan, 2014), the majority of the evidence suggests the use of spatial cues (such as head shadow and binaural processing cues) to segregate competing speech matures in the first few years of life in these contexts. Considered collectively, this suggests that children's ability to understand speech in multitalker environments relies on a variety of factors, including listener age, as well as the types of acoustic cues that are available to aid target/masker segregation.

Given that children have better hearing at EHFs compared to adults, and that EHFs have been shown to facilitate children's speech perception in quiet, the present study aims to determine the role of EHFs in children's speech-in-speech recognition. We previously demonstrated that access to EHFs improved speech-in-speech recognition for adults with normal hearing when the target talker was facing the listener and co-located maskers were facing away from the listener (Monson et al., 2019). We also found that an increase of only 15° in masker head orientation (from facing 45° to facing 60°) significantly improved performance. We took this experimental approach for two reasons. First, our experimental setup represents a more ecologically relevant listening scenario where the talker of interest is typically facing the listener, while background talkers are typically facing other directions. Second, we hypothesized that EHFs would become a more useful cue with this talker/masker mismatch in head orientation because of the well-known frequency- and direction-dependent radiation of acoustic energy from a talker (Chu and Warnock, 2002; Halkosaari et al., 2005; Kocon and Monson, 2018; Monson et al., 2012a; Rayleigh, 1908). That is, because low-frequency energy radiates fairly omnidirectionally around a talker, whereas increasingly higher frequency energy radiates with increasing directionality (i.e., towards the front of a talker), the rotation of a masker's head acts as a shallow low-pass filter with the cutoff frequency decreasing as the angle of rotation increases. Thus, the listener receives more EHF energy from the target talker (facing the listener) than from the maskers (facing other directions) in a real-world multitalker listening scenario, similar to what children may experience in a classroom environment. This EHF mismatch between the target and masker speech could serve as a segregation cue or provide EHF phonetic information for the target speech to facilitate speech-in-speech recognition.

The present study replicates this previous study with children, with the aim to assess the effects of development on EHF utility and head orientation cues for speech recognition. We hypothesized that, due to generally enhanced EHF hearing, children would derive greater benefit from EHFs than adults and that children would benefit from head orientation cues. We also questioned whether there would be an effect of child age on the degree of benefit from these cues. Determining the utility of EHFs and head orientation cues for children's speech-in-speech recognition will not only increase our understanding of the role of EHF in speech perception during development, but will also improve our knowledge of the mechanisms that children use to navigate complex auditory environments. Additionally, if children are more reliant on EHF cues than adults in these contexts, this could also have implications for children with high-frequency hearing loss.

2. Methods

2.1. Participants

Listeners were 39 children (ages 5.1-17.8 years, 19 female). All children were native speakers of American English and had normal hearing, with pure tone thresholds ≤ 20 dB HL for octave frequencies between 0.25 and 16 kHz in both ears (ANSI, 2018). Normal hearing was verified via audiometric hearing screening; individual audiograms were not obtained in order to complete all procedures within a single, one-hour laboratory visit. Exclusion criteria included known neurological disorders or developmental delays, as well as a history of ear disease. Adult data were taken from Monson et al. (2019) for comparison with the child data collected in the present study. Adult listeners consisted of 18 adults (ages 20-27 years, 14 female) with normal hearing, as indicated by pure tone audiometric thresholds ≤ 20 dB HL in both ears for octave frequencies between 0.5 Hz and 16 kHz and no history of hearing disorder.

2.2. Stimuli

The masker stimulus was a two-female-talker babble created using recordings taken from a database of high-fidelity (44.1-kHz sampling rate, 16-bit precision) anechoic multi-channel recordings, acquired with Class 1 precision microphones surrounding each talker from 0° (directly in front) to 180° (directly behind) (Monson et al., 2012a). Recordings from microphones located at 45° and 60° were used to make the masker stimuli. A semantically unpredictable speech signal was generated for each talker and each angle. The speech signals for each talker were then summed to create a two-talker masker stimulus with both talkers facing 45° and a two-talker masker stimulus with both talkers facing 60°. Target speech stimuli were the Bamford-Kowal-Bench (BKB) sentences (Bench et al., 1979) uttered by a single female talker, recorded in a sound-treated booth using a Class 1 precision microphone located at 0°, with 44.1-kHz sampling rate and 16-bit precision. For the low-pass filtered condition, all stimuli were low-pass filtered using a 32-pole Butterworth filter with cutoff frequency of 8 kHz. For the full-band condition, stimuli were low-pass filtered with cutoff frequency of 20 kHz.

2.3. Procedure

Custom scripts written in MATLAB (MathWorks) were used for signal processing and experimental control. The experiment was designed to replicate the adult study of Monson et al. (2019). Three modifications were made to accommodate child listeners: (1) increased the starting level (dB SNR) of the stimuli; (2) reduced the number of sentences per adaptive track; and (3) an experimenter sat inside the booth with the child. Additional details about these changes are noted in the text below. All recording materials and data for this study will be made available upon request. All experimental procedures were approved by the Institutional Review Board at the University of Illinois at Urbana-Champaign.

Co-located target and masker stimuli were presented to child participants seated in a sound-treated booth over a KRK Rokit 8 G3 loudspeaker at 1 m directly in front of the listener. Children were instructed to repeat back the target sentence, guessing when they were not sure. An experimenter remained in the booth during testing and scored each key word as correct or incorrect. The experimenter always sat behind the child and was able to monitor child to verify they were on task during testing.

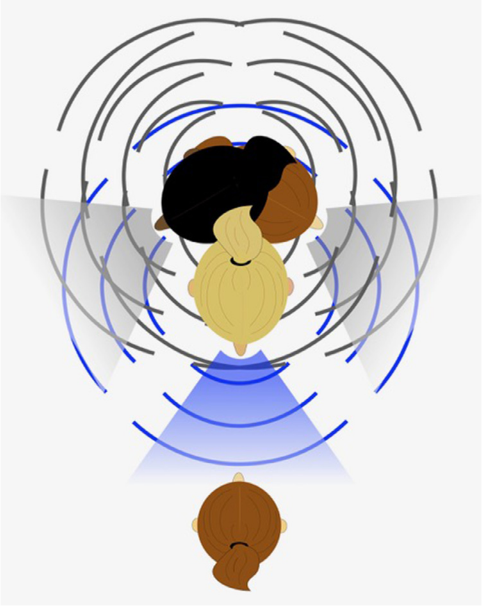

Fig. 1. Female target (blue) and two-female-talker masker (gray) arrangement simulated in this study. Bars represent omni-directional low-frequency radiation whereas shading represents highly directional EHF radiation.

Speech reception thresholds (SRT) were estimated using an adaptive procedure. The level of the two-talker masker was set at 70 dB SPL at 1 m, while the level of the target signal was adaptively varied. Two interleaved adaptive tracks were used, both with a one-down, one-up adaptive rule. For one track, the SNR was reduced if the child got one or more words correct; otherwise, the SNR was increased. For the other track, the SNR was reduced if the child got all words or all but one word correct; otherwise the SNR was increased. The word had to be an exact match to the keyword or it was marked as incorrect. The SNR was initially adjusted using a step size of 4 dB. This step size was then reduced to 2 dB after the first reversal.

There were 16 practice trials prior to testing to familiarize listeners with the task. During practice, both adaptive tracks started at 10 dB SNR (modified from 7 dB SNR for the adult experiment). All children were able to understand the instructions and successfully complete the practice phase. During testing, both adaptive tracks started at 7 dB SNR (modified from 4 dB SNR for the adult experiment). Each of the two tracks comprised 20 sentences (modified from 32 sentences for the adult experiment). Word level data from the two tracks were combined and fitted with a logit function with asymptotes at 0 and 100% correct. The SRT was defined as the SNR associated with 50% correct. Data fits were associated with r^2 values ranging from 0.64 to 0.99, with a median value of 0.89.

Two filtering conditions were tested: full band vs. all stimuli low-pass filtered at 8 kHz. Two masker head angle conditions were tested: both maskers facing 45° or both maskers facing 60° relative to the target talker (see Fig. 1). After the 16-sentence training block, the four conditions (2 filtering conditions × 2 masker head angles) were tested in separate blocks with block order randomized across participants. The starting sentence list number was randomized for each participant and continued in numerical order of the BKB sentence lists.

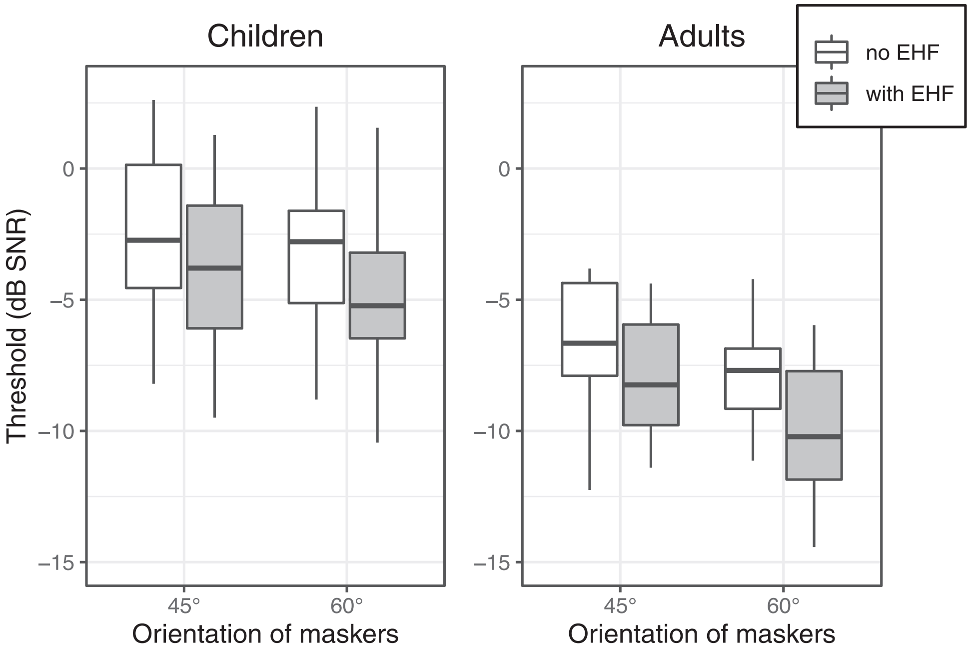

Fig. 2. Speech reception thresholds are shown for children (left) and adults (right) across all four experimental conditions. The range of performance that spans the 25th to the 75th percentile is shown for listeners in conditions with no EHF (unfilled boxed) and with EHF (gray boxes) for each masker head orientation. Horizontal lines within each box represent median scores; the 10th and 90th percentiles are shown by the vertical lines.

2.4. Statistical analyses

Statistical analyses were completed using R (R Core Development Team, 2019). Two approaches were used to analyze the data. To compare children and adults, the *afex* package (Singmann et al. 2020) in R was used to perform mixed model ANOVAs (*mixed* function), including the effects of EHF, head angle, and age group on SRTs. Age group was treated as a categorical variable in these analyses due to the assumption that development is at asymptote within the adult age group. P-values for these models were estimated using a parametric bootstrapping method, due to a violation of homogeneity of variance and small sample size in adult group. The second approach examined only the child data using child age as a continuous variable. For these analyses of child data, the nlme package for R (Pinheiro et al. 2016) was used to perform linear mixed-effects models with a random intercept for each subject to analyze the effects of age and condition on child SRT. For analyses of age as a continuous variable, a $\log_{10}$ transform was applied to age in years based on the rationale that maturation progresses more rapidly for younger children compared to older children (e.g., Buss et al., 2017). A significance level of $\alpha = 0.05$ was adopted.

Results

Fig. 2 shows SRTs in dB SNR for children (left) and adults (right) for all four conditions tested. Boxes indicate the range of SRTs across participants in each group spanning the 25th to 75th percentile. Horizontal lines inside each box indicate the median scores.

There was an overall trend for children's SRTs to be higher (poorer) than adults across all four conditions, consistent with previous data demonstrating that children are more susceptible than adults to the effects of a competing speech masker (Buss et al., 2019). There was also a trend for thresholds to be lower (better) in conditions with EHF as well as conditions with the greater head angle, irrespective of age. The average child SRT was higher in conditions that did not contain EHF (45° condition = -2.3 dB [SD = 2.9]; 60° condition = -3.3 dB [SD = 2.9]) compared to conditions with EHF (45° condition = -3.7 dB [SD = 3.0]; 60° condition = -5.0 dB [SD = 3.0]). Across both conditions, the mean improvement in SRT when EHF was present was 1.5 dB, which is comparable to the mean improvement in SRT for the adults (1.7 dB; Monson et al., 2019). As seen in Fig. 2, individual differences in children's SRTs were also observed, consistent with previous studies of children's speech-in-speech recognition (Buss et al., 2019; Flaherty et al. 2019; Wightman and Kistler, 2005; Wightman et al., 2006).

The assumptions of a mixed model ANOVA to compare age groups were tested. There were no significant outliers in the dataset, as inspected by a boxplot. Normality checks were carried out on the standardized residuals. Shapiro-Wilk test revealed that SRTs were normally distributed (p-value ranged from 0.319 to 0.955) for each combination of EHF, Angle and Age Group. Tests of homogeneity of variance by EHF and Angle condition were also conducted. Results indicated that variances were homogeneous between two groups under all EHF and Angle conditions (all p-values $>.05$) except for one condition (condition 4: No EHF, 60°, $p = 0.026$). See descriptive statistics in Table 1 for details. The homogeneity of the variance-covariance matrices assumption was met, as assessed by the Box's M statistic = 15.16 ($p = 0.19$). In addition, given that each within-subjects factor (EHF and Angle) has only two levels, sphericity assumption was met and sphericity test was unnecessary to be computed.

Due to the violation of homogeneity of variance and small sample size in adult group, we used a robust repeated measures ANOVA to compare SRTs between age groups. A mixed-effects model was fit using the afex command "mixed," and the values from the resulting ANOVA table are reported for that model. P-values were estimated using a parametric bootstrapping method. There was a main effect of age group ($\chi 2 = 30.40$, $p < 0.001$), a main effect of EHF ($\chi 2 = 61.95$, $p < 0.001$), and a main effect of masker head orientation angle ($\chi 2 = 46.86$, $p < 0.001$). The two- and three-way interactions between these factors were not signifi-

Table 1
Summary statistics of speech recognition thresholds (SRTs) and slope for adults and children for four masker conditions. The standard deviation (SD) for all mean SRTs are shown in parentheses.

Age Group	Masker condition	Mean SRT in dB, α (SD)	Mean slope in dB, β (SD)
Child, n=39	With EHF 45°	-3.7 (3.0)	2.6 (0.8)
	With EHF 60°	-5.0 (3.0)	2.9 (1.3)
	No EHF 45°	-2.3 (2.9)	2.5 (0.9)
	No EHF 60°	-3.3 (2.9)	2.5 (0.9)
Adult, n=18	With EHF 45°	-7.8 (2.3)	3.5 (0.8)
	With EHF 60°	-9.8 (2.7)	3.5 (1.2)
	No EHF 45°	-6.7 (2.5)	3.6 (0.9)
	No EHF 60°	-7.9 (1.7)	3.7 (1.3)

Note. The SRTs and slopes were estimated based on logit fits to data for each listener and condition.

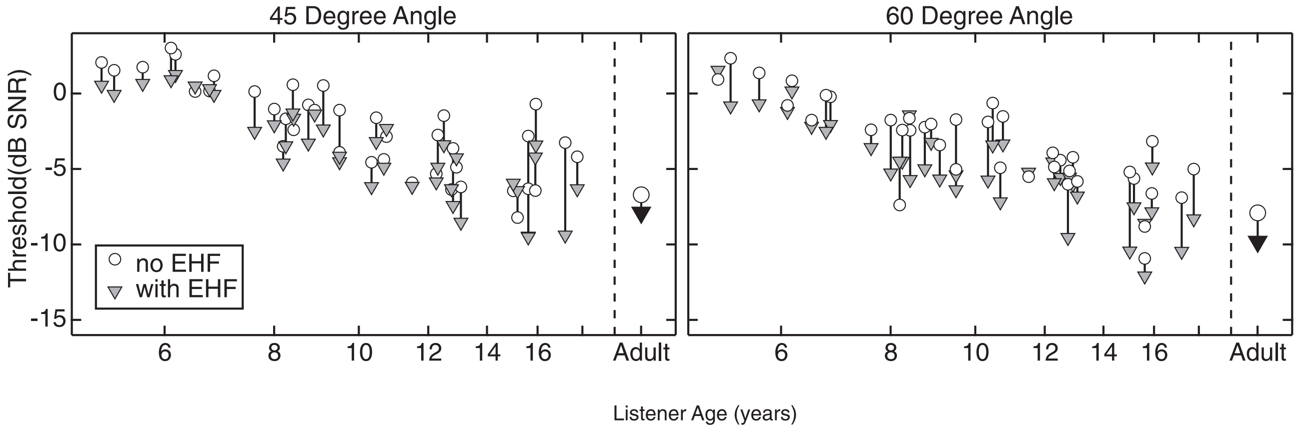

Fig. 3. The EHF benefit for individual children in the 45° angle (left) and the 60° angle (right) condition. Individual speech recognition thresholds are plotted in dB SNR as a function of child age on a log scale. Circles represent thresholds in the conditions with no EHF and gray triangles represent thresholds in the conditions with EHF. Adult data are presented on the far right, the circle represents the mean adult threshold in the conditions with no EHF and the black triangle represents the mean adult threshold in the conditions with EHF.

cant ($p > 0.243$). The lack of significant interactions indicates that the effects of EHF and of masker head orientation angle did not differ by age group.

The psychometric function slopes were also evaluated for children and adults across the different conditions (see Table 1 for values). Using the same robust repeated measures ANOVA with bootstrapping in order to account for violation of variance assumptions and the small sample size in the adult sample, we found no difference in psychometric function slopes across filtering conditions, ($\chi 2$ =0.86, p = 0.353), or angle conditions, ($\chi 2$ =1.12, p = 0.314), but there was a difference in psychometric function slopes between age groups, ($\chi 2$ =20.52, p < 0.001), indicating a steeper slope for children than adults.

The effects of EHF and head angle cues were also analyzed with child age as a continuous variable in a linear regression model. Adults were excluded from this analysis. This analysis was used to examine whether age would predict differences in the magnitude of benefit within the child group. Individual SRTs (in dB SNR) for the four conditions are shown in Figs. 3 and 4, plotted as a function of child age. Fig. 3 shows the effect of EHFs on SRTs for each of the masker head orientation angles. The circles show SRTs in the condition with no EHFs and the gray triangles indicate SRTs when EHFs were present. The line connecting the two symbols indicates the magnitude of benefit from the presence of EHFs. The data for the 45° angle are presented on the left and data for the 60° angle are on the right. There was a trend for decreased SRTs with increasing age in both conditions. With the exception of a few younger children in the 45° condition, the magnitude of difference resulting from the presence/absence of EHFs appears to be similar across the age range.

Table 2
Parameter estimates for the mixed effects regression model analyzing SRT as a function of condition and child age on a log scale.

	β	SE	df	t	p
Intercept	-3.98	1.01	111	-3.94	**0.0000**
EHF	1.16	0.63	111	1.86	**0.0325**
Angle	-1.62	0.63	111	-2.58	**0.0055**
Age	-8.18	2.87	37	-2.85	**0.0035**
EHF x Age	0.74	1.79	111	0.42	0.3387
Angle x Age	-0.01	1.79	111	-0.01	0.4976
EHF x Angle	0.28	0.40	111	0.73	0.2347
EHF x Angle x Age	0.02	1.13	111	0.02	0.4925

β = coefficient estimate, **SE** = standard error, **df** = degrees of freedom. Bolded values indicate significance at $\alpha = 0.05$.

Fig. 4 presents the effects of masker head orientation angle on individual SRTs. The circles show the individual SRTs in the condition with the 45° angle while the triangles indicate the SRTs for the 60° angle; the line connecting the two symbols indicates the masker head angle benefit. These head angle effects are shown for the conditions without EHF (left panel) and with EHF (right panel). Similar to Fig. 3, there was an overall trend for decreasing SRTs with increasing age. The majority of listeners showed improvements in SRTs when the head angle increased from 45° to 60°, with no apparent influence of age on this effect.

A linear mixed model was used to evaluate the significance of these trends. The model included the fixed effects of child age, filtering condition, and angle condition, as well as their interactions, The model output is shown in Table 2. There was a significant effect of EHF [β = 1.16, S.E. = 0.63, $t(111)$ = 1.86, p = 0.0325], a significant effect of masker head orientation angle [β = -1.62, S.E. = 0.63, $t(111)$ = -2.58, p = 0.0055],and a significant effect of

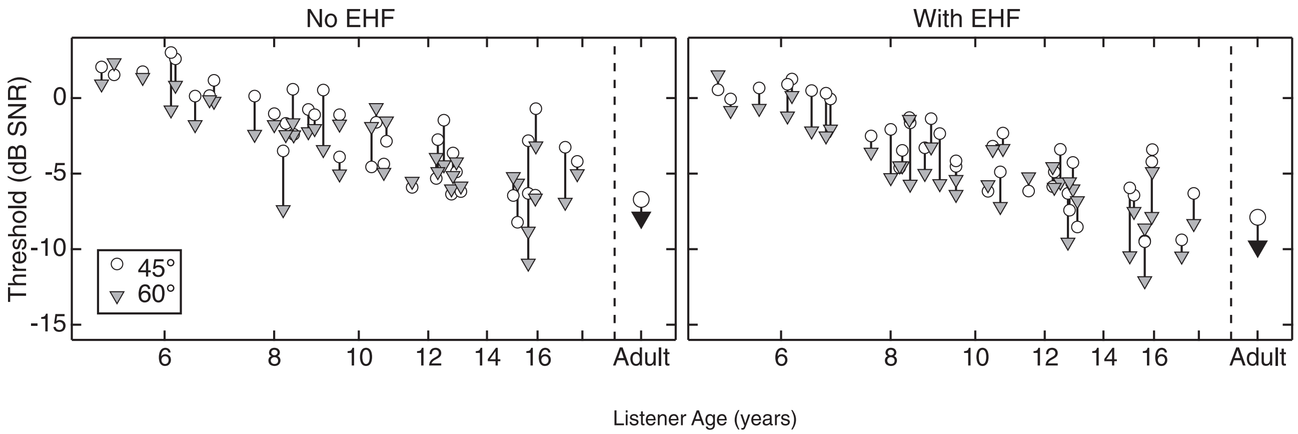

Fig. 4. The individual masker head angle benefit for children in conditions without EHF (left) and conditions with EHF (right). Individual speech recognition thresholds plotted in dB SNR as a function of child age on a log scale. Circles represent thresholds in the conditions with 45° masker head angle and gray triangles represent thresholds in the conditions the 60° masker head angle. Adult data are presented on the far right, the circle represents the mean adult threshold in the conditions with 45° masker head angle and the black triangle represents the mean adult threshold in the conditions the 60° masker head angle.

Table 3
Parameter estimates for the mixed effects regression model analyzing psychometric function slope as a function of condition and child age on a log scale.

	β	**SE**	**df**	**t**	**p**
Intercept	1.99	0.69	111	2.90	**0.0045**
EHF	0.29	0.43	111	0.66	0.5085
Angle	0.74	0.43	111	1.71	0.0903
Age	0.21	1.96	37	0.11	0.9157
EHF x Age	0.46	1.23	111	0.38	0.7068
Angle x Age	0.88	1.23	111	0.71	0.4782
EHF x Angle	-0.37	0.27	111	-1.34	0.1815
EHF x Angle x Age	-0.46	0.78	111	-.059	0.5542

β = coefficient estimate, **SE** = standard error, **df** = degrees of freedom. Bolded values indicate significance at $\alpha = 0.05$.

age [β = -8.18, S.E. = 2.87, $t(37)$ = -2.85, p = 0.0035], but no interactions ($p > 0.23$). The age effect indicates that mean SRTs decreased with increasing age for all conditions. Performance was best in the conditions with EHF cues present and in conditions when the masker head orientation angle was 60°. The absence of any interactions indicates that the magnitude of benefit did not differ as a function of age. The one-tailed bivariate correlation between the magnitude of EHF benefit and age was $r = 0.15$ ($p = 0.183$) in the 45° condition and was $r = 0.18$ ($p = 0.136$) in the 60° condition. The one-tailed correlation between the magnitude of head orientation angle benefit was $r = 0.25$ ($p = 0.072$) in the condition without EHFs and was $r = 0.14$ ($p = 0.197$) in the condition with EHFs.

A separate linear mixed model with the fixed effects of child age, filtering condition, and angle condition found no difference in psychometric function slopes across child age [β = .021, S.E. = 1.96, $t(37) = 0.11$, $p = 0.9157$], filtering conditions [$\beta = 0.29$, S.E. = 0.43, $t(111) = 0.66$, $p = 0.5085$], or angle conditions [$\beta = 0.74$, S.E. = 0.43, $t(111) = 1.71$, $p = 0.0903$]. The model output is reported in Table 3.

Discussion

The present study examined the utility of EHFs and masker head orientation cues for children's speech-in-speech recognition. Due to children's enhanced EHF hearing, it was hypothesized that children's speech recognition would be impacted by EHFs to a greater extent than had previously been demonstrated in adults. The results revealed that children's speech recognition was impacted by EHFs, but contrary to our expectations, we found no evidence that children take advantage of these cues to a greater extent than adults. Children's SRTs were significantly elevated in conditions in which the stimuli were low-pass filtered to remove EHFs, as well as in conditions where the masker talkers were facing more toward the listener. However, the effect of EHFs on children's performance did not differ significantly from the adults tested in a previous study (Monson et al., 2019). Therefore, there is no indication that children's enhanced ability to *detect* EHFs provides enhanced ability to *use* EHFs in contexts with competing talkers. Likewise, there was no evidence for a relationship between age and the ability to use head orientation cues for speech-in-speech recognition.

Susceptibility to masking

Across all conditions, children showed a gradual improvement in SRTs with increasing age, supporting previous data demonstrating that young children are more vulnerable to interference from competing speech compared to older children and adults (Buss et al., 2017; Flaherty et al., 2019; Hall et al., 2002; Wightman and Kistler, 2005). The present study demonstrates that children's increased susceptibility to interference from competing speech also applies when using more ecologically valid stimuli in which the competing talkers are not directly facing the listener. Despite the observation that children can take advantage of EHFs and masker head orientation, the prolonged developmental trajectory across all conditions provides additional support that they are immature in their ability to recognize speech in a speech masker even when those cues are available.

Effects of EHFs on speech recognition

Although children generally have enhanced EHF hearing compared to adults, this did not result in children in the present study deriving a greater benefit from EHFs. Children as young as 5 years of age were able to take advantage of EHF differences between target and masker speech, benefitting to a similar magnitude as previously observed in young adults (Monson et al., 2019). These findings suggest that the ability to use EHFs in this context matures relatively early, similar to the ability to use cues such as a sex mismatch or a spatial separation between target and masker speech, both of which have been observed in children 4 years of age and younger (Ching et al., 2011; Garadat and Litovsky, 2007; Leibold et al., 2018). This is in contrast to some other acoustic cues, such as differences in F0 or vocal tract length, which do not appear to impact younger children's speech recognition to the same degree as older children and adults (Flaherty et al., 2019; Flaherty et al., 2020). This adds to the mounting evidence that children's speech-in-speech recognition performance is influenced by the specific cues that are present in a given situation, with some cues being more beneficial than others for younger children.

One potential reason that EHFs provide a benefit for both younger and older children is that EHFs serve as a sufficiently salient segregation cue for listeners. That is, when EHF cues are present in the target, but not in the masker, they may serve as a grouping cue that can facilitate the listener's ability to group together the low-level information of the target speech separately from the competing masker speech. Given that EHFs are partly coherent with low-frequency cues (Crouzet and Ainsworth, 2001), they may facilitate segregation of low-frequency information in the target speech (Trine and Monson, 2020). EHFs may have also improved children's speech-in-speech recognition by providing additional phonetic cues for the target speech. The phonetically distinct spectral cues present in EHFs (Monson et al., 2012b; Vitela et al., 2015) may enhance the listener's ability to recognize the target speech containing EHFs (Trine and Monson, 2020). This idea is consistent with previous studies demonstrating that children rely on redundant acoustic information when perceiving speech, such as requiring greater bandwidth to recognize bandpass-filtered speech (Mlot et al., 2010; Stelmachowicz et al., 2001). This requirement for greater (or better quality) acoustic information is thought to be related to children's limited experience with speech and language, as well as other cognitive factors, such as working memory and attention, which are also maturing during childhood (see Leibold and Buss, 2019 for a review).

Whether EHFs aid in binding together low-frequency information and/or provides phonetically distinct spectral energy, the present data suggest that enhanced EHF hearing does not necessarily lead to an enhanced impact of EHFs on children's speech recognition. This is consistent with recent data demonstrating that children's sensitivity to a cue does not necessarily indicate its utility in competing speech environments. For example, for children with normal hearing, voice F0 discrimination thresholds are not predictive of their ability to utilize large voice F0 differences between competing talkers (Flaherty et al., 2019; Flaherty et al., 2020). Although children may be more sensitive to EHFs in quiet, they may not be able to take full advantage of them in complex listening situations.

In addition to immature segregation and selective attention abilities, another reason that children may not have benefited to a greater extent from EHFs than adults is that children appear to be immature in their ability to recognize speech based on spectrotemporally sparse cues (Buss et al., 2017). That is, when listening to speech in the presence of a competing speech masker, children are less capable of using the low-level speech cues that become available when fluctuations in the masker speech cause brief moments in which the SNR is more favorable, a process commonly referred to as glimpsing (Buss et al., 2017; Sobon et al., 2019; Zekveld et al., 2013). Therefore, despite having better EHF hearing, children may be less able to take advantage of EHF glimpses to recognize speech than adults because of limitations in their glimpsing ability. Limitations in glimpsing are supported by the slope comparisons between children in the present study and the adults tested previously using the same procedure and stimuli (Monson et al., 2019). The slope comparisons indicated a steeper psychometric function slope for children compared to adults, regardless of EHF or masker head angle, consistent with prior studies comparing speech-in-speech recognition between children and adults (Buss et al., 2017; Miller et al., 2018; Sobon et al., 2019). Children's sentence recognition showed rapid improvement as SNR increased, whereas adults showed more gradual improvements at less favorable SNRs. Adults' performance is consistent with the ability to use glimpses of low-level speech cues at relatively difficult SNRs, resulting in shallower psychometric function slopes. Children, on the other hand, unable to rely on glimpses to the same extent as adults, showed poor performance at low SNRs but a dramatic, or steeper, improvement in speech recognition once the SNR is greater than 0 dB.

Effects of head orientation on speech recognition

Like adults, children as young as 5 years of age were able to take advantage of a change in masker head orientation for improved speech-in-speech recognition. Further, there was no evidence for development of this ability as the auditory system matures. This finding is striking because the magnitude of change in masker head angle was only 15°, providing a small but highly significant improvement of 1.3 dB in the full-band condition. This change in head orientation is much smaller than the minimum audible change in head orientation (relative to a 0° head orientation) for adults, which is approximately 41° (Monson et al., 2019). Notably, this small change in masker head orientation primarily reduces speech spectral levels at EHFs (Monson et al., 2012a), thus it may be that taking advantage of this subtle change requires EHF hearing, which children have. When taken into consideration with the findings of children's early development of localization abilities (Litovsky, 2005), this finding of sensitivity to head orientation could indicate that general spatial awareness abilities develop relatively early in life.

Limitations

One limitation of this study was that pure tone thresholds were not obtained for individual children. Individual thresholds, instead of a hearing screening, would have permitted us to examine whether individual variability observed in children's SRTs were associated with individual differences in EHF threshold. Although children generally have better EHF hearing than adults, children can be diagnosed with high-frequency hearing loss for a variety reasons and children who are unable to perceive EHFs would be unable to take advantage of EHF cues. Given that EHF hearing is susceptible to otitis media with effusion (Cordeiro et al., 2018; Hunter et al., 1996) and that EHF hearing loss in some of those cases is permanent (Margolis et al., 2000), some very young children may show EHF hearing that is similar to the average 40- to 50-year-old adult (Hunter et al., 1996). This could potentially explain some of the large individual differences in performance that are reported in studies of speech-in-speech recognition in children (Bonino et al., 2013; Buss et al., 2019; Flaherty et al., 2019; Wightman and Kistler, 2005). In addition, individual differences in performance could also be partially explained by individual child differences in language skills and working memory (McCreery et al., 2017, 2019), although this is not consistently shown across all studies (see Magimairaj et al., 2018). It is possible these measures could have partially explained performance and thus should be included in future studies. Regardless, the present results indicate that EHFs are useful to children in complex listening situations and therefore should be examined further.

5. Conclusions

The present study evaluated the impact of limiting access to EHF energy in speech during a multitalker listening environment. Due to the directional nature of EHFs, head orientation of the competing talkers was also considered, similar to natural listening environments where the target faces the listener and other talkers are facing other directions. The present results demonstrated that EHF energy in the speech signal above 8 kHz is beneficial to children. While speech recognition occurred in the absence of EHFs, the presence of EHF in the speech signal improved overall performance. A small change in masker head orientation likewise improved speech recognition performance. Contrary to our hypothesis, despite children's increased sensitivity to EHFs relative to adults, children did not benefit to a greater degree than adults from these cues. These current findings demonstrate that EHFs are useful not only for localization, head orientation discrimination, and phoneme identification, but they also play a role in speech-in-speech understanding for school-age children as young as 5 years of age. This provides support for the mounting evidence in favor of EHFs playing a more important role in speech perception than historically considered (see Hunter et al., 2020 for a review). Given that previous studies of the utility of EHFs for children have focused on EHF pure-tone audibility, the present results are the first to demonstrate the utility of EHFs *per se* for children's speech-in-speech recognition. These findings have implications for real-world listening situations for children (e.g., in a classroom) and the potential for provision of higher frequency amplification. Future directions should explore the relationship between EHF thresholds and speech-in-speech recognition for children, investigating how EHF hearing loss in children could affect speech recognition in complex auditory scenes.

Acknowledgements

The authors thank Amber Dorn and Jasmine Thakkar for assistance with data collection. We would also like to thank Sa Shen for her assistance with statistical analyses. This work was supported the Department of Speech and Hearing Science at the University of Illinois at Urbana-Champaign.

Author Contribution

Mary Flaherty: Conceptualization, methodology, data collection, writing-Original draft preparation, formal analysis. **Kelsey Libert**: Investigation, Writing- reviewing and editing. **Brian Monson**: Conceptualization, methodology, software, Writing- Original draft preparation, reviewing and editing.

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