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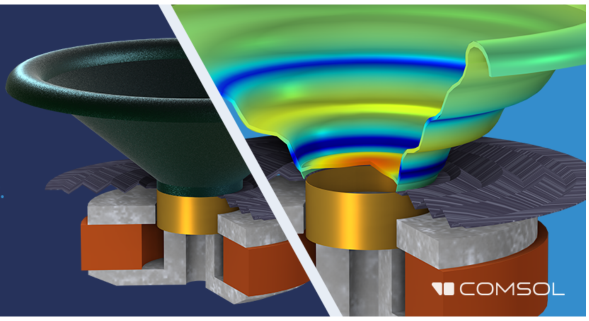

JASA ARTICLE

Suprathreshold auditory processes in listeners with normal audiograms but extended high-frequency hearing loss[a)]

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ABSTRACT:
Hearing loss in the extended high-frequency (EHF) range (>8 kHz) is widespread among young normal-hearing adults and could have perceptual consequences such as difficulty understanding speech in noise. However, it is unclear how EHF hearing loss might affect basic psychoacoustic processes. The hypothesis that EHF hearing loss is associated with poorer auditory resolution in the standard frequencies was tested. Temporal resolution was characterized by amplitude modulation detection thresholds (AMDTs), and spectral resolution was characterized by frequency change detection thresholds (FCDTs). AMDTs and FCDTs were measured in adults with or without EHF loss but with normal clinical audiograms. AMDTs were measured with 0.5- and 4-kHz carrier frequencies; similarly, FCDTs were measured for 0.5- and 4-kHz base frequencies. AMDTs were significantly higher with the 4 kHz than the 0.5 kHz carrier, but there was no significant effect of EHF loss. There was no significant effect of EHF loss on FCDTs at 0.5 kHz; however, FCDTs were significantly higher at 4 kHz for listeners with than without EHF loss. This suggests that some aspects of auditory resolution in the standard audiometric frequency range may be compromised in listeners with EHF hearing loss despite having a normal audiogram.
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I. INTRODUCTION

Hearing in the extended high-frequency (EHF) range (>8 kHz) may be impaired for some listeners despite a normal audiogram. EHF hearing loss appears to be widespread among young normal-hearing adults. Motlagh Zadeh *et al.* (2019) reported that 56% of young adults (18–30 years of age; $n = 78$) had EHF hearing loss even when mean audiometric thresholds at standard frequencies (0.25–8 kHz) were <16 dB hearing level (HL) for all of the participants and <10 dB HL for most participants. Likewise, Mishra *et al.* (2022a) found that 19% of adults (19–38 years of age; $n = 222$) had EHF hearing loss even when mean audiometric thresholds were <10 dB HL. Recent studies have also shown that EHF hearing loss can affect masked speech perception despite clinically normal audiograms (e.g., Braza *et al.*, 2022; Mishra *et al.*, 2022b; Monson *et al.*, 2019; Motlagh Zadeh *et al.*, 2019; Polspoel *et al.*, 2022; Saxena *et al.*, 2022; Trine and Monson, 2020). This perceptual consequence of EHF hearing loss has been observed across multiple speech stimuli (digits, words, and sentences), masker types (broadband noise, speech-shaped noise, multi-talker babble, and competing talkers), and methods of measurement (e.g., headphones vs sound-field and adaptive vs fixed signal-to-noise ratio). Many listeners with EHF loss report difficulty listening in background noise (Mishra *et al.*, 2022a; Motlagh Zadeh *et al.*, 2019). Saxena *et al.* (2022) showed that listeners with EHF loss report reduced functional hearing abilities, as characterized by the speech, spatial, and qualities of hearing scale (SSQ; Gatehouse and Noble, 2004). In the present study, we address the effects of EHF hearing loss on some aspects of auditory perception at suprathreshold hearing levels.

The basic auditory mechanisms associated with EHF hearing loss are not fully understood. One relevant mechanism proposed by Wright in Hunter *et al.*, (2020) was that impaired EHF hearing reduces input, which is essential for the accurate functioning of mechanisms acting at lower frequencies. Badri *et al.* (2011) found broadened auditory filter bandwidths [∼1.3 times larger equivalent rectangular bandwidths (ERBs)] at 2 kHz in listeners with normal audiograms but elevated EHF thresholds relative to controls. Reduced frequency selectivity within the standard audiometric frequency range suggests that EHF hearing thresholds may be a marker of subclinical outer hair cell (OHC) damage despite clinically normal audiograms. In addition, otoacoustic emission studies suggest reduced emission

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[a)] This paper is part of a special issue on Perception and Production of Sounds in the High-Frequency Range of Human Speech.

[b)] Electronic mail: srikanta.mishra@austin.utexas.edu levels at lower frequencies in individuals with EHF hearing loss (Hunter *et al.*, 2021; Mishra *et al.*, 2022a,b).

Sensitivity to amplitude modulations is important for speech understanding (Houtgast and Steeneken, 1985; Shannon *et al.*, 1995; Zeng *et al.*, 2005). Likewise, the ability to detect small changes in frequency is critical for perception of complex sounds such as speech and music (Horst, 1987; Vonck *et al.*, 2021; de Weirdt, 1988). Poor frequency discrimiantion has been associated with hearing loss (e.g., Turner, 1987; Phillips and Hall, 2000) and, in turn, deficits in speech performance (e.g., Divenyi and Haupt, 1997). Given the relationship between EHF hearing and masked speech understanding (e.g., Braza *et al.*, 2022; Mishra *et al.*, 2022b; Monson *et al.*, 2019; Motlagh Zadeh *et al.*, 2019; Polspoel *et al.*, 2022; Saxena *et al.*, 2022; Trine and Monson, 2020), it is reasonable to assume that EHF hearing loss might be associated with poorer temporal processing and frequency resolution. The knowledge regarding the influence of EHF hearing loss on these basic auditory resolution measures has important implications for understanding suprathreshold deficits in the presence of a normal audiogram. This would also contribute to the psychoacoustic basis of speech-in-noise deficits observed in EHF hearing loss.

The aim of the present study was to test the hypothesis that EHF hearing loss is associated with suprathreshold deficits in the standard frequency range despite a normal audiogram. We measured amplitude modulation detection thresholds (AMDTs) and frequency change detection thresholds (FCDTs) in listeners with and without EHF hearing loss; all of the listeners had clinically normal audiograms. If EHF hearing loss is associated with subclinical OHC damage at the standard frequencies, as suggested by otoacoustic emissions studies (Hunter *et al.*, 2021; Mishra *et al.*, 2022a,b), one might expect higher (poorer) FCDTs, especially at high frequencies, where place cues are important as excitation patterns may be broadened. If EHF loss is additionally associated with the loss of inner hair cells, synapses, and/or primary auditory neurons, one might expect higher (poorer) AMDTs as a result of degraded temporal fidelity. For either of these putative mechanisms, there would be little-to-no effect on standard frequency hearing thresholds.

II. METHODS

A. Participants

Forty-five participants (ages 17–39 years old) with clinically normal audiograms ($\leq$20 dB HL for all of the audiometric frequencies between 0.25 and 8 kHz) and normal "A"-type tympanograms were enrolled in this study. All were otologically healthy, and none had a significant history of traumatic noise exposure or ototoxicity. Following a case-control design, participants were categorized into "EHF-normal" and "EHF-loss" groups based on hearing thresholds at 10, 12.5, and 16 kHz. EHF hearing loss was defined as hearing thresholds >20 dB HL at any EHFs in either ear. There were 28 participants in the EHF-normal group (mean age = 22 ± 4.23 years old; females = 15), and 17 participants in the EHF-loss group (mean age = 24 ± 5.50 years old; females = 7; unilateral EHF loss = 5). There was no significant difference in age between the EHF-normal and EHF-loss groups ($t_{34.8} = -1.66$, $p = 0.11$). The study protocol was approved by the University of Texas Rio Grande Valley Institutional Review Board (IRB-22-0025).

B. Psychoacoustic tests: AMDTs and FCDTs

All of the psychoacoustical tests were implemented using a customized version of AngelSound.[1] Stimuli were presented diotically at 70 dB sound pressure level (SPL) via HDA200 headphones (Sennheiser, Wedemark, Germany) connected to an external audio device (Scarlett 2i2, Focusrite, High Wycombe, UK) in a sound booth. During testing, participants responded using a mouse connected to a laptop computer.

AMDTs were measured for two carrier frequencies: 0.5- and 4-kHz. Carriers were sinusoidally amplitude-modulated (AM) at 20 Hz. AMDTs were measured using a three-alternate-forced-choice (3AFC) task. Participants were instructed to listen to three tones. The target interval contained the AM stimulus (probe) while the other intervals contained non-AM stimuli (reference). The order of the reference and probe stimuli was randomized across trials. The durations for the AM and non-AM stimuli were 0.5 s and a 10-ms onset and offset ramp was applied to all of the stimuli. The interstimulus interval was 0.5 s. The modulation depth, m (where $m = 1$ corresponds to 100% modulation), was adapted according to the correctness of the response. The initial modulation depth was -15 dB (20 log m with respect to 100% AM depth). The initial step size was 3 dB. After two reversals, the step size was reduced to 1 dB. The adaptive run was terminated after eight reversals or a maximum of 35 trials; if the maximum number of trials was reached without achieving 8 reversals, the run was discarded and the test was repeated. The AMDT threshold for each carrier frequency was calculated as the average of the last six reversals in terms of modulation depth (dB).

FCDTs for 0.5 and 4 kHz were adaptively measured using a 3AFC task (two-down/one-up). The probe stimulus contained an upward change in base frequency (0.5 or 4 kHz) 500 ms after the stimulus onset; the range of frequency change was 0.1%–100%. The transition at 500 ms occurred at 0° phase (zero crossing) to prevent audible transient clicks (Dimitrijevic *et al.*, 2008). The stimuli were 1 s long, and a 10-ms onset and offset ramp was applied to all stimuli. During testing, the three intervals were presented, and the participant responded by clicking on the interval that was different. The probe frequency was adjusted according to the correctness of the response. The step size was 0.1% when the probe frequency difference was 0%–0.5%; 0.5% for thresholds when the probe frequency difference was 0.5%–2.0%; and 2% when the probe frequency difference was >2%. The initial frequency difference for the probe was 16% above the reference frequency. The adaptive run was terminated after 8 reversals or a maximum of 35 trials; if the maximum number of trials was reached without achieving 8 reversals, the run was discarded, and the test was repeated. The detection threshold at each reference frequency was calculated as the average of the last six reversals ($\Delta f/F$ in percent).

C. Statistics

Because of non-normal distributions according to Shapiro-Wilks tests ($p < 0.05$), group differences (EHF-normal vs EHF-loss) in hearing thresholds were compared at each audiometric frequency using Mann-Whitney rank sum tests. Because of non-normal distributions, according to Shapiro-Wilks tests ($p < 0.05$), group differences and frequency effects (carrier frequency for AMDTs and base frequency for FCDTs) were analyzed using Kruskal-Wallis analysis of variance (ANOVA) on ranked data with *post hoc* comparisons using Dunn's method. FCDT data were log-transformed before analysis. Multiple linear regression and simple linear regression were used to identify predictors of psychoacoustic performance. All of the effects are reported as significant at $p < 0.05$. Cohen's d was used to compute effect sizes for significant effects. Statistical analyses were conducted using Sigmaplot (version 14) and SPSS (version 22).

III. RESULTS

Figure 1 shows mean hearing thresholds for the EHF-normal and EHF-loss groups as a function of audiometric frequency. Note that one participant in the EHF-loss group had no response at the audiometer's maximum level (60 dB HL) at 16 kHz. Paired t-tests at each test frequency showed no significant difference in thresholds between the left and right ears, therefore, the data were averaged across ears at each frequency. The mean pure-tone average (PTA) threshold across all standard audiometric frequencies (0.25–8 kHz) was 10.3 ± 1.1 and 10.9 ± 1.9 dB HL for the EHF-normal and EHF-loss groups, respectively. The mean PTA threshold across all EHFs (10–16 kHz) was 11.0 ± 2.1 and 20.7 ± 12.7 dB HL for the EHF-normal and EHF-loss groups, respectively. Mann-Whitney rank sum tests showed that thresholds were significantly higher for the EHF-loss than for the EHF-normal group at 8 kHz ($p = 0.003$), 12.5 kHz ($p = 0.016$), and 16 kHz ($p < 0.001$).

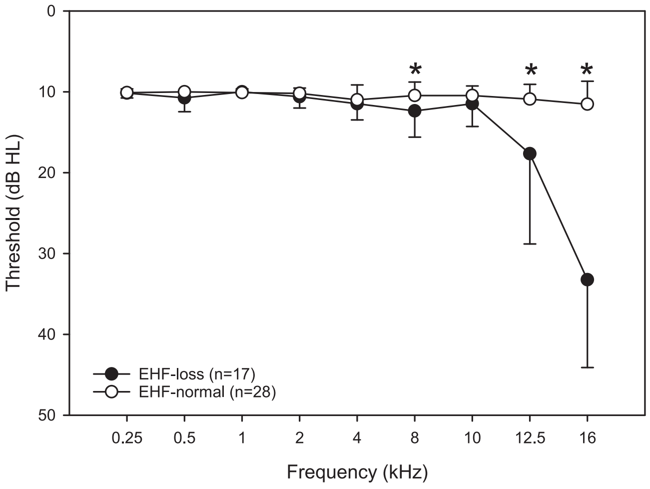

FIG. 1. Mean hearing thresholds as a function of audiometric frequency for the EHF-normal and EHF-impaired groups. Note that there was no response for one participant in the EHF-loss group at 16 kHz (i.e., threshold > 60 dB HL). The error bars represent the standard deviation; note that the error bars are shown in only one direction for brevity. The asterisks show significant differences between the EHF-normal and EHF-loss groups ($p < 0.05$).

Figure 2 shows violin plots of AMDTs for the EHF-normal and EHF-loss groups for the two carrier frequencies. The mean AMDTs for the EHF-normal group were −23.9 ± 2.7 and −15.9 ± 5.6 dB for the 0.5 and 4 kHz carriers, respectively. The mean AMDTs for the EHF-loss group were −22.6 ± 4.3 and −15.8 ± 5.3 dB for the 0.5 and 4 kHz carriers, respectively. A Kruskal-Wallis ANOVA was performed on AMDT data with condition (EHF-loss/0.5 kHz carrier, EHF-loss/4 kHz carrier, EHF-normal/0.5 kHz carrier, and EHF-normal/4 kHz carrier) as the factor. Results showed a significant effect of condition (dF = 3, $H = 35.9$, $p < 0.001$). *Post hoc* pairwise comparisons showed that AMDTs were significantly higher (poorer) for the 0.5 kHz carrier than for the 4 kHz carrier for the EHF-loss ($p = 0.008$) and EHF-normal groups ($p < 0.001$). There was no significant difference between the EHF-loss and EHF-normal groups with the 0.5 or 4 kHz carriers ($p > 0.05$ for all comparisons).

Figure 3 shows violin plots of FCDTs for the EHF-normal and EHF-loss groups for the two base frequencies. The mean FCDTs for the EHF-normal group were 0.7 ± 0.3% and 0.5 ± 0.2% for the 0.5- and 4-kHz base frequencies, respectively. The mean FCDTs for the EHF-loss group were for 0.8 ± 0.4 and 0.7 ± 0.2 for the 0.5- and 4-kHz base frequencies, respectively. A Kruskal-Wallis ANOVA was performed on FCDT data with condition

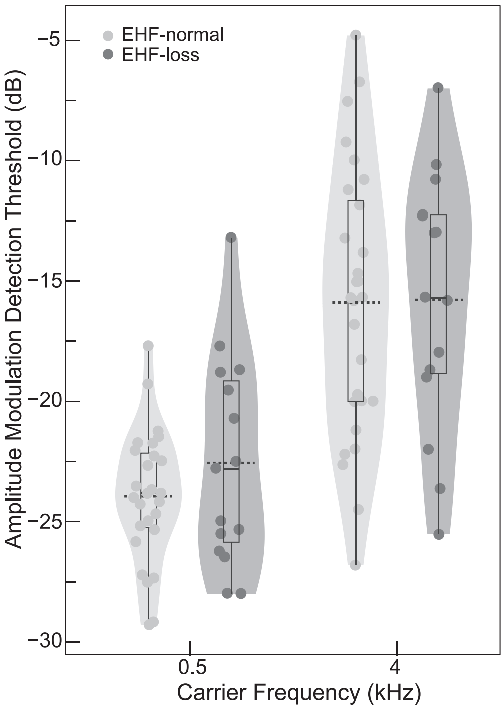

FIG. 2. Violin plots of AMDTs for the EHF-normal (light gray) and EHF-loss groups (dark gray) for the 0.5 and 4 kHz carriers. The boxes show the 25th and 75th percentile, the dashed line shows the median, and the error bars show the 5th and 95th percentiles.

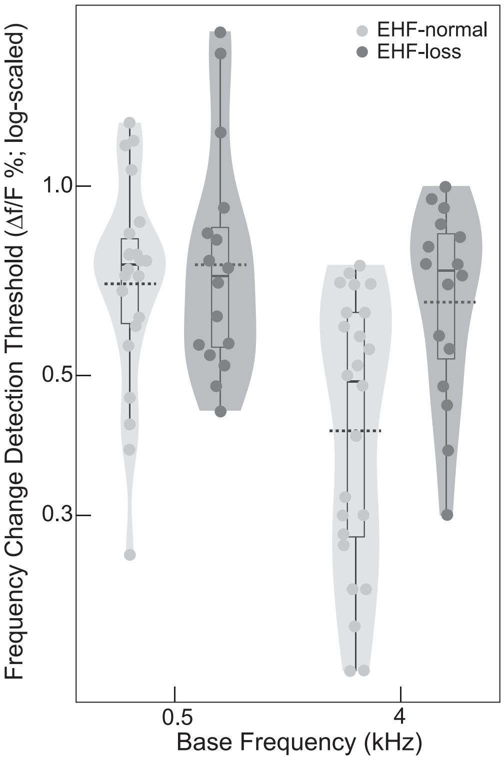

FIG. 3. Violin plots of FCDTs for the EHF-normal (light gray) and EHF-loss groups (dark gray) for the 0.5- and 4-kHz base frequencies; *y* axis is log-scaled. The boxes show the 25th and 75th percentiles, the dashed line shows the median, and the error bars show the 5th and 95th percentiles.

(EHF-loss/0.5-kHz base frequency, EHF-loss/4-kHz base frequency, EHF-normal/0.5-kHz base frequency, and EHF-normal/4-kHz base frequency) as the factor. Results showed a significant effect of condition (degrees of freedom = 3, $H = 18.1$, $p < 0.001$). *Post hoc* pairwise comparisons showed that FCDTs were significantly higher (poorer) at 0.5 kHz than at 4 kHz only for the EHF-normal group ($p < 0.001$). At 4 kHz, FCDTs were significantly higher (poorer) for the EHF-loss than for EHF-normal group ($p = 0.012$; Cohen's $d = 1.09$) with no significant difference between the EHF-loss and EHF-normal groups at 0.5 kHz ($p > 0.05$).

Multiple linear regression was used to identify predictors of FCDTs at 4 kHz (the only psychoacoustic test that was sensitive to EHF loss). Predictors entered into the model included age at testing and thresholds at 4, 8, 12.5, and 16 kHz. Results showed that only thresholds at 16 kHz significantly predicted FCDTs at 4 kHz ($p = 0.021$). The remaining predictors did not contribute significantly to the model ($p > 0.05$). Subsequent linear regression (Fig. 4) showed a significant association between FCDTs at 4 kHz and thresholds at 16 kHz ($r^2 = 0.24$, $p = 0.001$).

IV. DISCUSSION

A. Overall findings

The present study examined the effects of EHF hearing loss on suprathreshold auditory perception in adult listeners with normal audiograms. The data only partially support the hypothesis that EHF hearing loss is associated with suprathreshold deficits in auditory perception in the standard frequency range despite a clinically normal audiogram. There was no statistically significant effect of EHF hearing loss on AMDTs for either carrier frequency (0.5 and 4 kHz) or for FCDTs at 0.5 kHz. However, EHF hearing loss had a significant adverse effect on FCDTs at 4 kHz. The magnitude of the effect was large. This effect could not be accounted for by age or hearing acuity (at 4 kHz) of the listeners. Interestingly, elevated hearing thresholds at 16 kHz were associated with higher FCDTs at 4 kHz. This finding raises the possibility that certain aspects of auditory resolution in the standard frequencies are compromised in listeners with EHF hearing loss despite having a normal audiogram.

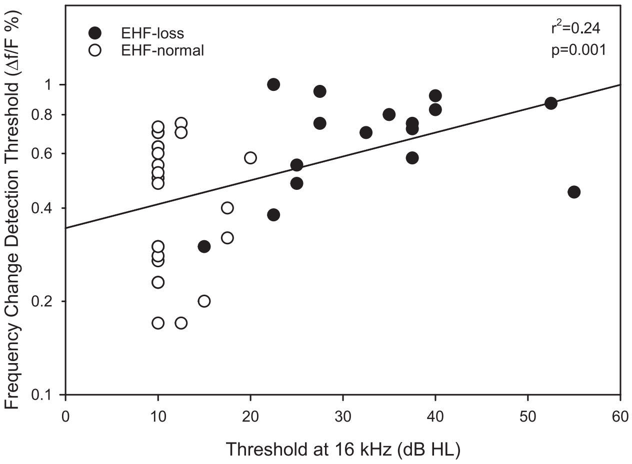

FIG. 4. FCDTs as a function of hearing threshold at 16 kHz for the EHF-normal and EHF-impaired groups; *y* axis is log-scaled. The diagonal line shows the linear regression performed on overall data; r^2 and *p* values are shown in the upper right corner.

B. Comparison with the literature

Previous studies show that EHF loss is associated with a small but significant elevation in hearing thresholds in the standard frequencies despite clinically normal thresholds (Mishra *et al.*, 2022a; Motlagh Zadeh *et al.*, 2019; Saxena *et al.*, 2022). The hearing thresholds at all standard frequencies except 8 kHz were indistinguishable between the listeners with EHF hearing loss and controls. At 8 kHz, the mean threshold was 2.4 dB higher for the EHF group compared to the EHF-normal group.

AMDTs and FCDTs measured in the present study are consistent with the relevant literature. Stone and Moore (2014) reported a significant effect of carrier frequency on AMDTs with higher (poorer) thresholds with a 6 kHz carrier than 3 or 4 kHz carriers. A similar effect of carrier frequency on slow-modulation AMDTs was reported by Vinay and Moore (2010). We also observed a similar effect in that AMDTs were higher with the 4 kHz than the 0.5 kHz carrier.

Frequency discrimination thresholds could vary with the method of measurement (Sek and Moore, 1995). Detecting a dynamic change in frequency is less dependent on cognitive factors, such as working memory, compared to static frequency discrimination (Buss *et al.*, 2014). The mean FCDTs at 0.5 and 4 kHz were 0.81% and 0.59%, respectively, for EHF-normal and EHF-loss groups combined, which are consistent with the data reported by Vonck *et al.* (2021).

C. EHF hearing loss and suprathreshold deficits

At low modulation rates (∼20 Hz), listeners with normal hearing and sensorineural hearing loss have similar AMDTs measured using sinusoidal or random modulations (Grose *et al.*, 2016; Koopman *et al.*, 2008; Moore and Glasberg, 2001; Shen and Lentz, 2010). In addition, there is no consistent effect of noise exposure on AMDTs reported for individuals with clinically normal audiograms (Prendergast *et al.*, 2017; Prendergast *et al.*, 2019; Stone and Moore, 2014; Vinay and Moore, 2010). We found no significant effect of EHF hearing loss on amplitude modulations for 0.5- and 4-kHz carrier frequencies. This suggests that EHF loss, perhaps reflecting early OHC damage, may not affect the mechanisms responsible for temporal encoding for listeners with clinically normal audiometric thresholds.

Previous studies have shown an association between sensorineural hearing loss and reduced frequency discrimination (e.g., Moore, 1996; Oxenham, 2008). In these studies, hearing impairment was only measured in the standard frequency range. In the present study, we observed poorer FCDTs at a frequency (4 kHz) two octaves lower than the frequency of hearing loss (16 kHz). A significant deficit for the EHF-loss group was observed for FCDTs only at the 4-kHz base frequency, suggesting that different mechanisms may underlie frequency discrimination at 0.5 and 4 kHz, and EHF hearing loss may selectively impair mechanisms that underlie frequency discrimination at 4 kHz. Although there is considerable debate about the upper limits of temporal fine structure encoding, it is generally accepted that phase-locking is active at 0.5 kHz and place-coding (i.e., sharpness of the excitation pattern) determines discrimination at 4 kHz in human listeners (Verschooten *et al.*, 2019). The higher (poorer) FCDTs at 4 kHz may be attributed to OHC dysfunction associated with broadened auditory filter bandwidths at standard audiometric frequencies. Although we did not measure filter bandwidths at standard frequencies, Badri *et al.* (2011) reported broadened auditory filter bandwidths at 2 kHz in listeners with elevated EHF thresholds despite a normal audiogram. In addition, several studies suggest that EHF hearing loss could be associated with subclinical OHC deficits that may be obscured by a standard audiogram, such as (1) reduced or absent otoacoustic emissions at standard frequencies in listeners with EHF hearing loss (Hunter *et al.*, 2021; Mishra *et al.*, 2022a,b), and (2) a slight elevation (approximately 2 dB, on average) in standard frequency hearing thresholds in listeners with EHF hearing loss compared to controls (Mishra *et al.*, 2022a,b; Motlagh Zadeh *et al.*, 2019; Saxena *et al.*, 2022).

D. Translational implications

The clinical audiogram (i.e., hearing thresholds measured from 0.25 to 8 kHz) is not known to be sensitive to subtle auditory damage. The audiogram can be normal in several conditions such as tinnitus, broadened auditory filters, and reduced otoacoustic emissions (e.g., Badri *et al.*, 2011; Hall and Lutman, 1999; Schaette and McAlpine, 2011). In addition, cochlear synaptopathy or hidden hearing loss may occur without any substantial change in the audiogram (Kujawa and Liberman, 2009). The present data suggest that FCDTs may be elevated even when the mean hearing threshold at 4 kHz was 12 dB HL for the EHF-loss group (note that 15 dB HL is a stricter clinical norm for adults). However, this deficit in auditory resolution was significantly predicted by the EHF threshold at 16 kHz. Thus, including EHFs in threshold audiometry could be beneficial for identifying subclinical OHC damage that may have perceptual consequences that might not be detectable with standard audiometric thresholds. Vonck *et al.* (2021) observed significant correlations between frequency discrimination at 4 kHz and speech recognition thresholds and the acoustic change complex (an obligatory cortical evoked potential). The present data suggest that elevated high-frequency FCDTs caused by EHF loss might negatively impact speech-in-noise recognition among listeners with otherwise normal audiograms.

Bharadwaj *et al.* (2019) predicted that basal cochlear damage could be associated with cochlear synaptopathy in relatively apical regions in humans. Liberman *et al.* (2016) suggested that EHF audiometry may be a marker for hidden hearing loss at lower frequencies. Although this study was not designed to measure cochlear synaptopathy, the lack of a significant effect of EHF hearing loss on AMDTs—a hypothesized perceptual feature of cochlear synpatopathy (Plack *et al.*, 2014)—may suggest an absence of hidden hearing loss due to synaptopathy in the present cohort.

There is considerable interindividual variability in frequency discrimination ability among normal-hearing listeners (Micheyl *et al.*, 2012). The present data suggest that some of this variability (at least for high frequencies) may be explained by hearing acuity at EHFs, which may represent OHC integrity in the standard audiometric range. Listeners with EHF hearing loss may have subclinical OHC deficits at standard frequencies despite a normal audiogram.

V. CONCLUSIONS

In this study, perception of amplitude modulation and dynamic changes in frequency were measured in adults with clinically normal audiograms but with or without EHF hearing loss. Results showed that EHF hearing loss had no effect on sensitivity to 20-Hz amplitude modulation for relatively low (0.5-kHz) or high carrier frequencies (4-kHz). EHF hearing loss was associated with poorer sensitivity to changes in frequency at high base rates (4 kHz) but not at low base rates (0.5 kHz). Sensitivity to changes in frequency at 4 kHz was significantly associated with audiometric thresholds at 16 kHz. This suggests an adverse perceptual consequence of EHF loss on frequency resolution in the standard frequency range. The results further suggest that audiometric thresholds in the standard frequency range may not predict suprathreshold hearing deficits.

[1] See http://angelsound.tigerspeech.com/ (Last viewed April 15, 2021).

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