Extended high-frequency hearing enhances speech perception in noise

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Young healthy adults can hear tones up to at least 20 kHz. However, clinical audiometry, by which hearing loss is diagnosed, is limited at high frequencies to 8 kHz. Evidence suggests there is salient information at extended high frequencies (EHFs; 8 to 20 kHz) that may influence speech intelligibility, but whether that information is used in challenging listening conditions remains unknown. Difficulty understanding speech in noisy environments is the most common concern people have about their hearing and usually the first sign of age-related hearing loss. Digits-in-noise (DIN), a widely used test of speech-in-noise perception, can be sensitized for detection of high-frequency hearing loss by low-pass filtering the broadband masking noise. Here, we used standard and EHF audiometry, self-report, and successively higher cutoff frequency filters (2 to 8 kHz) in a DIN test to investigate contributions of higher-frequency hearing to speech-in-noise perception. Three surprising results were found. First, 74 of 116 "normally hearing," mostly younger adults had some hearing loss at frequencies above 8 kHz. Early EHF hearing loss may thus be an easily measured, preventive warning to protect hearing. Second, EHF hearing loss correlated with self-reported difficulty hearing in noise. Finally, even with the broadest filtered noise (≤8 kHz), DIN hearing thresholds were significantly better ($P < 0.0001$) than those using broadband noise. Sound energy above 8 kHz thus contributes to speech perception in noise. People with "normal hearing" frequently report difficulty hearing in challenging environments. Our results suggest that one contribution to this difficulty is EHF hearing loss.

self-report | digits-in-noise test | pure-tone audiometry | listening in noise | high-frequency hearing

Normal pure-tone hearing thresholds as measured by the "gold standard" audiogram do not necessarily mean absence of pathology in the cochlea or central auditory nervous system (1–4). For example, there is evidence from animal and some human studies that noise exposure and aging are associated with loss of synapses between inner hair cells and cochlear nerve fibers before any depletion of hair cells or elevation of hearing thresholds occurs (3, 5–8). This cochlear "synaptopathy" occurs first at higher frequencies (3) and has been hypothesized to contribute to a range of difficulties known in human studies by various names including "obscure auditory dysfunction" (9) and "hidden hearing loss" (10). Following the failure of standard audiometry to detect such early signs of neurodegeneration, some studies have examined the diagnostic utility of extended high-frequency (EHF) audiometry in detection of hidden hearing loss caused by noise exposure, ototoxicity, and aging (11–13).

Although frequencies below 6 kHz provide the phonetic information required for speech perception in quiet, substantial evidence suggests there is salient information in the higher-frequency regions that may affect speech intelligibility (1, 2, 14–18). Shaw et al. (19) were among the first to propose that poor speech perception in noise may be a result of an EHF hearing loss. In 9 adults who complained of difficulty understanding speech in noise they found elevated mean high-frequency (10 to 20 kHz) thresholds.

More generally, standard pure-tone audiometry is unable to predict with precision the level of difficulty a person will have listening to speech in a challenging environment (17, 20–22). Speech signals have a spectrotemporal complexity that changes with limited predictability over time. Accurate speech coding and recognition requires multiple auditory discrimination skills (23). Pure-tone detection also uses minimal cognitive resources, in contrast to suprathreshold speech perception, especially in the presence of competing noise (22). Speech-in-noise tests allow us to objectively and reliably measure speech recognition abilities (24–28). This is typically achieved by presenting speech segments, whole words, or sentences to listeners against a simultaneous background of broadband (BB) random noise or multitalker "babble." A "speech reception threshold" (SRT) is defined as the speech signal/noise ratio (SNR) at which speech is correctly recognized in 50% of presentations.

Digits (0 through 9) have been used as stimuli in several speech perception tests (29–31) and in clinical screening (5, 24, 32–34). Digits are highly overlearned stimuli that are easily recognized by a wide range of people, including young children (35) and nonnative language speakers (36). Randomized digit triplets have a low probability of all being correctly guessed and provide more accurate and reproducible SRT estimates than other speech test materials, including nondigit words, single digits, and sentences

Significance

Understanding speech in noisy environments is an essential communication skill that varies widely between individuals and is poorly understood. We show here that extended high-frequency (EHF) hearing, beyond the currently tested range of clinical audiometry, contributes to speech perception in noise. EHF hearing loss is common in otherwise normally hearing young adults and predicts self-reported difficulty hearing speech in noise. The data suggest that EHF hearing is a long sought missing link between audiometry and speech perception and may be a sensitive predictor of age-related hearing loss much earlier in life when preventive measures can be effectively deployed.

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(5, 33, 37). Previous studies have reported a strong correlation between DIN-SRTs and audiometric "pure-tone average" (PTA) measures in adult listeners of mixed hearing ability (5, 23, 24, 33). DIN can be administered as a rapid, reliable, fully automated self-test accessible by telephone (including smartphone apps) or internet, and there is no requirement for sound-attenuating booths or other clinical equipment (5, 23, 38–40).

Results

Audiological Testing. To investigate contributions of higher-frequency hearing to speech-in-noise perception we first recruited 116 adult listeners (18 to 65 years old [y/o], M = 29.5, SD = 9.1; 67 females) with normal hearing sensitivity in both ears across the standard range of frequencies (≤20-dB hearing level [HL]; 0.25 to 8 kHz; Fig. 1*A*). However, 74 of these listeners (64%) had elevated EHF thresholds (10 to 16 kHz; >20-dB HL, Fig. 1*B*) at one or more frequencies, in one or both ears, as defined by the International Organization for Standardization (ISO 389-5, 2006). Retesting of thresholds at 14 and 16 kHz in 11 of the 116 listeners showed high reliability of EHF thresholds for both ears (left: Pearson's $r = 0.96$; right: $r = 0.97$) and frequencies (14 kHz: $r = 0.99$; 16 kHz: $r = 0.93$). For nearly all listeners, EHF hearing thresholds, indexed by standardized HL, were higher than those in the standard range.

Listeners were mostly younger adults, categorized by age into 5 groups (Fig. 1*C*). Nonparametric analysis of variance (ANOVA) showed no significant differences between the youngest 3 age groups for PTA-EHF hearing thresholds (PTA of 8 EHFs = 4 frequencies × 2 ears). The 31 to 40 y/o group had significantly higher thresholds than the 2 youngest groups ($P < 0.05$), and the thresholds of the oldest group (41 to 65 y/o) were significantly higher ($P < 0.0001$) than all 4 other groups. Nevertheless, 44 of 78 listeners (56%) who were less than 30 y/o had at least 1 elevated EHF threshold (>20-dB HL).

Despite responding to a recruitment advertisement that called for "normal hearing," in a background questionnaire that asked: "Do you find it difficult to follow a conversation if there is a background noise (such as TV, radio, children playing)?" (22), 39 of the 116 listeners (34%) reported difficulty. To analyze the relationship between self-reported difficulty and EHF hearing loss, participants were divided into 4 categories (Fig. 1*D*) based on PTA-EHF thresholds. Listeners self-reporting difficulty hearing in noise were significantly more likely to be placed in the higher categories, indicating EHF hearing loss (Fig. 1*E*; χ^2 analysis; $P < 0.0001$).

By selection, these 116 listeners had sensitive thresholds in the standard frequency (SF) range, with mean thresholds (PTA-SF from 0.25 to 8.0 kHz, both ears) all <16-dB HL, and most <10-dB HL (Fig. 1*F*), well below a currently accepted upper limit of normal hearing (20-dB HL; American Academy of Audiology [AAA] Clinical Practice Guidelines, 2015). Nevertheless, PTA-SF was correlated with PTA-EHF ($r = 0.56$, $P < 0.0001$), raising the possibility that standard frequency hearing might be driving apparent sensitivity to EHF hearing. Remarkably, however, 25 of the 39 listeners (64%) reporting difficulties had PTA-EHF >20-dB HL, but mean PTA-SF of just 9-dB HL, further suggesting it is their EHF hearing that accounts for their difficulty.

Receiver operating characteristic (ROC) curves were calculated for PTA-SF and PTA-EHF to quantify and contrast self-report in this sample (Fig. 1*G*). The cutoff value on the ROC curve was the PTA (in dB HL) with the highest sensitivity and specificity. PTA-EHF had greater area under the curve (ROC area = 0.81, cutoff = 22.8-dB HL), compared to PTA-SF (ROC area = 0.71, cutoff = 4.7-dB HL), showing the superior ability of EHF hearing thresholds to predict difficulty hearing in noise in this "normal" hearing sample. Both PTA-EHF threshold and prevalence of self-reported hearing difficulty increased with age (Fig. 1*H*). Note, however, the prevalence of both PTA-EHF hearing loss (>20-dB HL) and self-reported difficulty among the younger listeners.

DIN Testing. In our implementation of the DIN, digits were recorded and "homogenized" by adjusting the level of each digit to the mean SRT of all digits at 50% intelligibility (5). Homogenized digits were presented as triplets in noise through headphones (Fig. 2*A*) in an audiological sound booth. Extended bandwidth spectrograms of the digits revealed a surprisingly rich representation of EHF energy (Fig. 2*B* and *SI Appendix*, Fig. S1). Noise maskers are used in DIN testing to simulate real-world interfering sounds. Typically, the noises are BB (Fig. 2*C*) and relatively unmodulated, made by summing the spectrum of individual digits. Low-pass filtering the noise makes higher-frequency energy in the digits more audible, thus sensitizing the DIN for detection of high-frequency hearing loss. For example, a previously used 1.5-kHz low-pass noise masker produced higher sensitivity and specificity (81 to 93%) for detection of high-frequency hearing loss among a clinical sample than a broadband noise (5). Here, we extended these methods using low-pass filtered noise with higher cutoff frequencies (2, 4, and 8 kHz) in addition to broadband noise (Fig. 2*C*). We predicted that low-pass filtering with successively higher-frequency cutoffs would further sensitize the DIN to successively higher-frequency information in the standard audiometric range. We also hypothesized that acoustic information above the 8-kHz limit of standard audiometry would contribute to speech perception in noise.

Sixty of the listeners (19 to 62 y/o, M = 29.6, SD = 10.7; 39 females) who provided audiometric data were tested using DIN with each of the 4 filters. As noise bandwidth broadened (Fig. 2*C*) mean SRT increased (became poorer, Fig. 2*D*) as predicted, due to masking the higher-frequency components of the digits. However, as hypothesized, even the broadest low-pass filter (8-kHz cutoff) produced an SRT that was significantly better (mean 3.2 dB more negative; $F_{1,\,118} = 187.7$, $P < 0.0001$) than that resulting from the unfiltered, broadband noise. We therefore concluded that sound energy above the upper frequency limit of the standard audiogram contributed significantly to the intelligibility of the digits.

For the power spectra in Fig. 2*C*, Butterworth filters (41) that are 3 dB down at the cutoff frequency were used to filter the noise. It is possible that the better mean SRT we found for the 8-kHz cutoff was due to the reduced noise energy (at −3 dB) and just below this frequency. To check this possibility, we collected additional SRTs using another filter (a Chebyshev filter) (41) that does not allow additional energy to pass at 8 kHz. The results did not differ significantly ($P = 0.9$) from those obtained using the Butterworth filter (*SI Appendix*, Fig. S2). It is also possible that slight gaps between the low-frequency arms of the filtered noises and the BB noise, created by the addition of the attenuated, same BB noise to the filtered maskers, may have facilitated lower-frequency sound perception. One of these gaps, in the 3.5- to 6-kHz frequency region of the 8-kHz noise (Fig. 2*C*), had the potential of confounding interpretation. To check whether the better mean SRT found for the 8-kHz low-pass filter was due to this gap, we corrected for the differences in spectra by adding independent samples of the attenuated BB noise to each low-pass filtered noise (*SI Appendix*, Fig. S3) and collected additional SRTs using the updated noise spectra. The results confirmed the consistent benefit of the 8-kHz low-pass filter over BB noise (mean SRT 2.6 dB more negative, $P < 0.0001$).

Thirty-four of the 60 listeners (57%) in the DIN sample had elevated EHF hearing threshold (>20-dB HL) at one or more frequencies in one or both ears. Of those 34, 22 listeners had a PTA-EHF threshold >20-dB HL. PTA-EHF across all listeners was significantly related to broadband, BB-SRT (Fig. 2*E*); those with more sensitive EHF hearing had more sensitive BB-SRT. However, the relation between PTA-EHF and SRT-8 kHz was

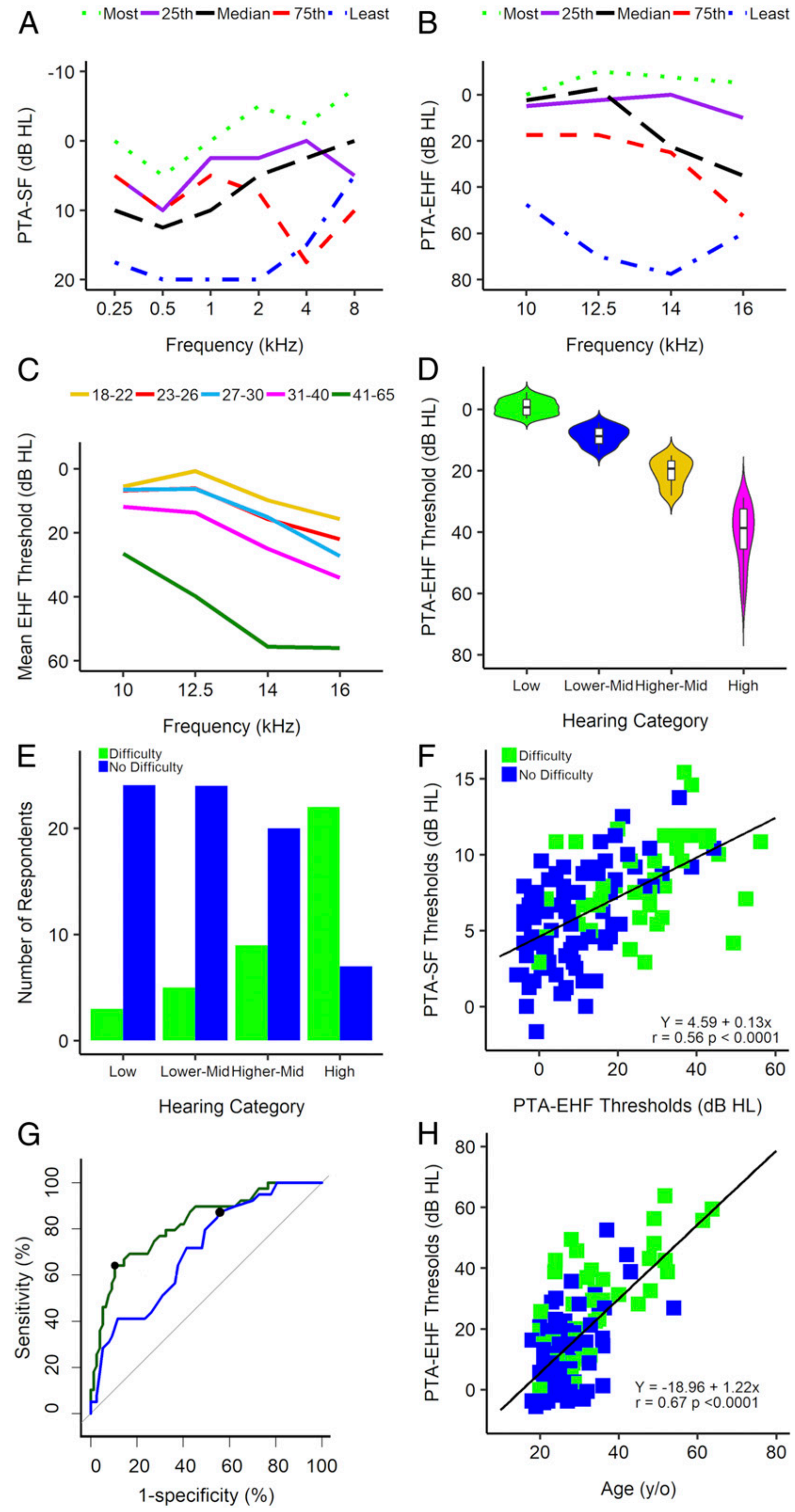

Fig. 1. Hearing loss and hearing difficulty. Mean hearing thresholds of both ears for (*A*) standard frequency (PTA-SF) and (*B*) extended high-frequency (PTA-EHF) ranges. Black lines show median thresholds of both ears for all 116 listeners. Colored lines show mean thresholds of both ears for the individuals with most and least sensitive hearing, and those closest to the 25th and 75th percentiles. (*C*) Mean EHF thresholds of both ears for 5 age groups: 18 to 22 y/o (n = 29), 23 to 26 (n = 25), 27 to 30 (n = 25), 31 to 40 (n = 24), and 41 to 65 (n = 13). (*D*) PTA-EHF thresholds (pure-tone average of 8 EHFs = 4 frequencies × 2 ears) in 4 categories: low, lower mid, higher mid, and high (n = 29 in each category). Violin plots show kernel probability density of thresholds, boxes are interquartile range (with median), and whiskers are 1.5 times the interquartile range. (*E*) Rated self-reported difficulty listening in noise by hearing category. (*F*) Correlation between PTA-SF and PTA-EHF thresholds for individual listeners with and without self-reported difficulty listening in noise. (*G*) ROC curves showing test characteristics of the PTA-SF and PTA-EHF based on self-reported difficulty hearing in noise. The filled black dots correspond to the optimal cutoff of each test. (*H*) Correlation between age and PTA-EHF thresholds for individual listeners with and without self-reported difficulty listening in noise.

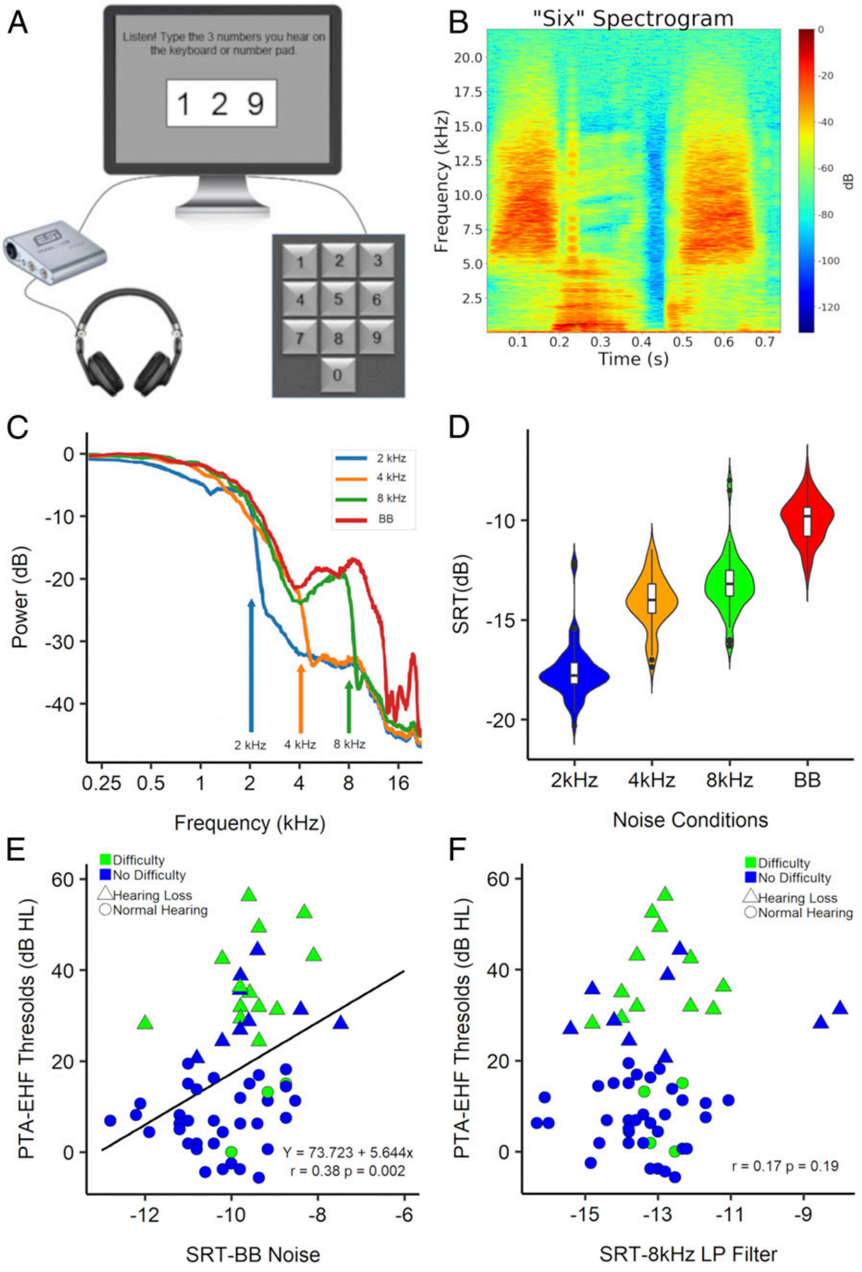

Fig. 2. EHF hearing improves speech perception in noise. (*A*) DIN test. (*B*) Spectrogram of the digit "6" showing substantial energy above 8 kHz. Spectrograms of all digits (0 through 9) are shown in *SI Appendix*, Fig. S1. (*C*) Four masking noise power spectra were unfiltered (broadband, BB) or had upper frequency cuts at 2, 4, or 8 kHz. (*D*) Speech reception threshold (SRT) improved with lower frequency noise spectrum cut. (*E* and *F*) Correlation between PTA-EHF thresholds with BB and 8-kHz low-pass filtered noise conditions for listeners with and without self-reported difficulty hearing in noise. Each data point indicates mean SRTs of individual listeners. Regression equations and lines, and correlations fit to all data.

nonsignificant (Fig. 2*F*). We initially found this result perplexing, because we expected the 8-kHz noise filter to provide better differentiation between listeners with and without EHF hearing loss. It is important to note, however, that SRT-8 kHz performance was markedly better across PTA, with a mean SRT of −13.2 dB, relative to the BB-SRT performance (mean = −9.9 dB). There was no significant correlation between PTA-SF and either BB-SRT (r = 0.17) or 8 kHz-SRT (r = 0.09). As discussed in further detail below, we suggest the pattern of results in Fig. 2 *E* and *F* is due to lack of EHF masking by the 8-kHz filtered noise relative to the BB noise.

Listeners in the DIN sample who self-reported difficulty hearing in noise had higher mean EHF thresholds than those reporting no difficulty, as found in the larger sample (df = 59, $P < 0.0001$; cf. Fig. 1*F*). Twelve of 13 listeners with self-reported difficulty and elevated EHF thresholds (green triangles in Fig. 2 *E* and *F*) had bilateral EHF hearing loss (2 to 4 elevated hearing thresholds in each ear >20-dB HL).

Discussion

Listeners in this study all had normal audiometry (≤20-dB HL) in the standard frequency range (0.25 to 8 kHz) but around two-thirds had some evidence of EHF hearing loss (>20-dB HL) and about one-third reported difficulty hearing in everyday noisy situations. We found that the extent of the specific EHF hearing loss was related to the number of individuals self-reporting difficulty hearing and to the DIN-SRT. Our results also showed that EHF hearing loss and self-reported difficulty are already widespread among people in their 20s, suggesting that, even at this young age, speech perception in challenging conditions is reduced. Healthy people in their 20s are sometimes assumed to have the most sensitive hearing of any age group (42). However, hearing very high-frequency tones is most sensitive in young children and hearing becomes progressively less sensitive throughout the remainder of life (43). For example, a downward decline for hearing 20 kHz starts from 4 to 6 y of age (43, 44).

Given the apparent competence of communication in most young adults, how important are EHFs for hearing? Self-report is playing an increasingly prominent role in hearing assessment. The recently recognized complexity of contributions to hearing, both within and outside the conventionally defined auditory system (1, 45), reduces the likelihood that one, or even a small number of tests is likely to capture the full experience of hearing. We found here that EHF hearing loss is related to self-reported difficulty hearing in noisy environments. Other studies have found similar poor EHF hearing in young adults reporting high levels of music exposure and otherwise normal audiograms (3).

Our findings also revealed that providing supplementary EHF stimulation in the DIN speech-in-noise task improved SRTs in individuals both with and without EHF hearing loss. In a study investigating the relationship between SRT in noise and self-reported hearing disability, it was found that adults who self-reported "difficulty" following conversation in noise had 2.7-dB poorer mean DIN-SRT than adults with "good" ability listening in noise (25). These and other data (33, 37) suggest that the mean 3.2-dB improved intelligibility found here after allowing access to EHFs is likely to be of substantial functional significance. To our knowledge, this is direct, sample-based evidence that EHFs enhance speech hearing ability. It adds to previous studies that have combined EHF with lower-frequency stimuli (46), used only lower-frequency stimuli (4 to 8 kHz) (47, 48), or presented clinical reports on individual cases (16).

A potential confusion in *Results* was the finding of relative lack of SRT sensitivity, particularly 8 kHz-SRT, to EHF thresholds (Fig. 2 *E* and *F*). At first pass, this finding appears to contradict the major conclusion that EHF hearing enhances speech perception in noise. However, using the 8-kHz filtered noise, EHF information is still available to those with mild EHF hearing loss without the 20-dB shadow cast across EHFs by the BB masker. With the extra BB masking, those with better EHF thresholds retained a (modest) SRT advantage, because the masking was preventing access to EHF information for those with mild EHF hearing loss.

Another possibility is that the relation between PTA-EHF and BB-SRT is driven by responses of EHF neurons to energy in the standard frequency bands. This could occur if the tails or low-frequency rising slopes of tuning curves of EHF neurons normally contribute to the SRT for elements of the speech signals within the standard frequency range (49). When EHF neurons have elevated thresholds, it may effectively remove that contribution to hearing in the standard frequency range, leading to an increase in SRT that could then be incorrectly attributed to EHF hearing loss. We think the tails are unlikely to contribute because they would have too high thresholds relative to the measured SRTs (−8 to −18 dB relative to a 65-dB SPL noise). It is harder to rule out such a contribution for the low-frequency rising slopes of tuning curves of EHF neurons having a characteristic frequency (CF) near the 8-kHz cutoff. We suppose that human tuning curves of neurons with a CF around 10 kHz, the lowest EHF contributing to the PTA-EHF, might make a small contribution. However, most of the EHF hearing loss is occurring at higher frequencies. To examine further the contribution of EHF energy, a future experiment could filter EHF information from the digits, rather than the noise, and probe effects on SRT.

Benefits of the DIN include that it is procedurally very unchallenging, as discussed above, and it is available in self-administered forms, delivered on-line (33) or by smartphone (38). A screening test takes only about 3 min. However, there has also been concern that, since English digits may be largely distinguished based on their low-frequency vowel formants, the DIN could be insensitive to higher-frequency hearing loss (36). The results from this and a previous study (5) clearly show this concern is unfounded. Sensitizing the DIN to high-frequency hearing by using low-pass filtered noise and broad-spectrum digits improved performance of people with normal hearing.

Another concern about the digits is that they represent a "closed-set" (i.e., limited) word corpus (33). In some respects, this could make the digits less generalizable to real life situations, since "open-set" words or sentences are more representative of those situations (33). On the other hand, the digits are an extreme form of simple speech stimuli that were selected originally for an easy, portable, and self-administered screening test of hearing loss (26), a role this research was in part designed to enhance. More than any other speech-in-noise test of which we are aware, the DIN has been shown to correlate strongly with audiometry (33). This is likely because highly overlearned digits are stimuli that result in very sensitive and reproducible SRTs. They have a relative lack of cognitive (22) or linguistic influence, resulting in a test with, for example, minimal practice effects (33). Further research using less predictable target stimuli may be helpful to understand perceptual mechanisms underlying the self-report data presented here in addition to other aspects of typical listening such as context (50).

The sensitivity of the DIN to EHF cues found here was unexpected. One reason is that speech spectrograms are typically shown only to 4 to 8 kHz (51, 52), reflecting a view that higher frequencies are of low energy and unimportant for speech perception. When we extended the spectrogram of the digits used in this study beyond 8 kHz, we found considerable EHF energy. It appears that this energy is used by listeners with sufficient EHF hearing to extract useful cues to identify the digits in noise. Together with the finding of widespread EHF hearing loss, this may help explain why many people with normal standard audiograms have difficulty hearing in noisy places.

Clinical Implications. Following on from the great success of "universal" neonatal hearing screening that has reduced dramatically the age at which hearing aids and cochlear implants are fitted to infants with hearing impairment (53), there has been considerable discussion among policy makers as to whether there should be a "universal hearing screen" in adulthood (54). This discussion has centered around the tendency for people in their 50s and older to delay by many years the age at which they start using hearing aids. If the criterion for hearing loss is extended to the EHF range of frequencies, many more people, perhaps the majority of adults, might be considered as candidates for some form of hearing intervention.

This raises the question of whether very early EHF "hearing loss" is a harbinger of more disabling hearing loss in the standard range of frequencies and later in life ("presbycusis"). It has long been known that hearing loss in older people starts at the higher frequencies within the standard range and moves steadily toward the lower frequencies, considered most vital for speech perception (55, 56). For EHF, thresholds are only measurable in about half the older population, presumably reflecting individual differences in sensitivity highlighted here as well as the high absolute sound levels needed to achieve ISO standards for hearing level in the average listener. Where it can be measured, the pattern of correlation between age, hearing level, and frequency is consistent with a downward trend of the upper limit of EHF hearing that precedes presbycusis (57, 58). It seems likely that EHF hearing earlier in life could therefore be a sensitive predictor of later disability. Further research is needed to test this prediction, but a universal EHF hearing screen (59) in late adolescence or early adulthood could lead to identification of vulnerable individuals and more timely advice regarding prevention and conservation among susceptible individuals.

The mechanisms of EHF hearing loss are presumably similar to those elsewhere in the frequency spectrum and may result from genetic effects, noise, ototoxicity, infections, and aging (60). However, the early appearance and high prevalence of EHF hearing loss suggest possible additional mechanisms. One such known mechanism is early childhood otitis media with effusion (OME) (61). OME is very common from birth to 5 to 6 y of age (62). It is associated with EHF hearing loss and with ototoxicity in the extreme basal end of the cochlea (63). Another possibility is that some form of hidden hearing loss, such as a widespread neuropathy throughout the cochlea, affects speech perception in noise. Recently, Wu et al. (64) investigated cochlear neuropathy in a temporal-bone study of 29 humans aged 0 to 89 y at autopsy. Their findings showed that neurodegeneration of auditory nerve peripheral axons in the aging ear outpaces loss of inner hair cells and spiral ganglion somata across the audiometric standard frequency range, likely contributing to age-related difficulty hearing in noise. Insufficient data were available to test predictions from this study concerning EHF hearing loss beginning in childhood, but it is notable that interpolation from the available data suggested possible neurodegeneration by the age of 20.

A possible reason for the historic neglect of EHF hearing in clinical audiology may be that hearing aids do not typically have the ability to provide amplification at higher frequencies. New technologies are helping correct this shortcoming (18, 65), but further research and wider recognition of the benefits of EHF hearing are also required.

Methods

Participants. A female Midwestern American English speaker was recruited to record the digits. A total of 116 listeners of average age 29.5 y (SD = 9.1; 67 females) with normal hearing sensitivity ($\leq$20-dB HL) in the conventional range of audiometric frequencies (0.25 to 8 kHz) were recruited via flyers distributed in the community and at Cincinnati Children's Hospital Medical Center (CCHMC) and the University of Cincinnati. Seventy people (M = 29 y/o, SD = 10, 44 female) from the original 116 participants participated in DIN testing. Ten of these people performed only homogenization testing (see below), and 60 participated in the DIN part of the main study. All participants were paid and gave written informed consent. The consent form and the experimental procedures were approved by the CCHMC Institutional Review Board.

Audiological Testing. Conventional pure-tone audiometry was performed using an Interacoustics Equinox 2.0 model audiometer calibrated to ANSI 3.6 2010. Participants were tested in a double-walled sound booth (Acoustic Systems, Austin, TX) meeting criteria of the American National Standards Institute (ANSI) S3.1–1999 for audiometric test rooms. Air conduction thresholds were obtained using Sennheiser HDA300 circumaural headphones.

DIN Testing. The DIN test was developed based on the method described by Vlaming et al. (5), Smits et al. (33), and Potgieter et al. (38).

Speech Stimuli and Masking Noise. A list of 20 triplets was made from 10 digits (0 through 9), where each digit occurred 2 times at each position (a, b, and c). A BB speech-shaped noise masker was developed by obtaining an average frequency spectrum across all digits. Low-pass noise versions of the masker were constructed using a 10th-order Butterworth low-pass filter with 3 different cutoff frequencies (2, 4, and 8 kHz), summed with a 15-dB attenuated version of the original broadband noise. Noise was started 100 ms before and ended 100 ms after each triplet presentation and was continuous between the test triplets. To achieve equal intelligibility, digits were homogenized with respect to SRT. For this purpose, the average of scores for each digit at each position was subtracted from the overall mean SRT to give the decibel difference required for homogenizing the digits. The difference in decibel was then transformed into a factor to multiply with the digit waveforms to ensure that each digit had a 50% chance of being recognized correctly at the same SNR (see *SI Appendix* for more details on development and homogenization of the DIN test).

DIN Procedure. A random set of 25 triplets was made from the homogenized digits. The triplets were presented diotically over Sennheiser (Wedemark, Germany) HD 25-1 headphones via a Maya 22 USB sound card in a double-walled sound booth (Acoustic Systems) meeting criteria of ANSI S3.1–1999 for audiometric test rooms. A one-down, one-up adaptive procedure was used to obtain the SRT. In this procedure, following each correct response, the SNR level was reduced by 2 dB, and following each incorrect response, the SNR was increased by 2 dB. All 3 digits had to be correct for the trial to be a correct response. Total presentation duration was, again, 3.25 s The initial SNR level was −4 dB, about 8 to 10 dB above the expected SRTs for normal hearing listeners in each test condition. SRT was estimated as average SNR of the final 19 of 25 total trials.

Analysis. R software (version 3.4.2) was used for statistical computing and graphics. One-way ANOVA and Tukey post hoc test were used for group comparisons. All P values were 2-sided, and a P value of <0.05 was accepted as the statistical significance level. ROC curves were calculated using the pROC package in R software.

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