Extending the High-Frequency Bandwidth and Predicting Speech-in-Noise Recognition: Building on the Work of Pat Stelmachowicz

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ABSTRACT

Recent work has demonstrated that high-frequency (>6 kHz) and extended high-frequency (EHF; >8 kHz) hearing is valuable for speech-in-noise recognition. Several studies also indicate that EHF pure-tone thresholds predict speech-in-noise performance. These findings contradict the broadly accepted "speech bandwidth" that has historically been limited to below 8 kHz. This growing body of work is a tribute to the work of Pat Stelmachowicz, whose research was instrumental in revealing the limitations of the prior speech bandwidth work, particularly for female talkers and child listeners. Here, we provide a historical review that demonstrates how the work of Stelmachowicz and her colleagues paved the way for subsequent research to measure effects of extended bandwidths and EHF hearing. We also present a reanalysis of previous data collected in our lab, the results of which suggest that 16-kHz pure-tone thresholds are consistent predictors of speech-in-noise performance, regardless of whether EHF cues are present in the speech signal. Based on the work of Stelmachowicz, her colleagues, and those who have come afterward, we argue that it is time to retire the notion of a limited speech bandwidth for speech perception for both children and adults.

KEYWORDS: extended high frequency, speech perception, speech in noise

Recent work has demonstrated that adults and children utilize the entire upper end of the frequency range of hearing, including extended high-frequency (EHF) hearing (above 8 kHz), for speech-in-noise recognition. Furthermore, several studies indicate that EHF pure-tone thresholds predict speech-in-noise performance. Findings from these recent studies stand

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Tribute to Patricia Stelmachowicz; Guest Editor, Ryan W. McCreery, Ph.D.

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in contrast to the broadly accepted "speech bandwidth" that has historically been limited to below 8 kHz. This growing body of work has been greatly influenced by the work of Pat Stelmachowicz, whose research was among the first to (1) rigorously measure EHF pure-tone thresholds across the lifespan and (2) question the validity of the traditionally defined speech bandwidth, particularly for female talkers and child listeners.

In the present article, we review the relevant literature from a historical viewpoint, demonstrating the link between the most recent research and the work of Stelmachowicz and her colleagues. We also present a reanalysis of previous data collected in our lab assessing the relationship between standard and EHF pure-tone thresholds and speech-in-noise performance.

HISTORICAL CONTEXT AND WORK OF PAT STELMACHOWICZ

Early days of research on speech bandwidth were focused on and driven by the need to improve telephony and other communication systems.[1] The primary objective of this research was to determine which frequencies in speech conveyed the most information for speech recognition. These early efforts resulted in the articulation index (AI),[2] now called the speech intelligibility index (SII),[3,4] a model used to predict speech recognition based on the audibility and importance of different frequency bands of a speech signal. One feature of the AI that persisted in early iterations of the SII was that bands above approximately 6 kHz either provided or were assumed to provide negligible contributions for speech recognition.[2,3,5,6] It is important to recognize that the earliest studies, on which later studies were founded, were limited in their ability to accurately capture and reproduce the highest frequencies due to recording and transducer limitations.[1] Additionally, perhaps due to the motivation to improve telecommunication, early studies did not often consider under what ecological conditions hearing at the highest frequencies might be useful for speech perception.

During this era, there was also interest in improving accuracy of high-frequency audiometry to measure auditory function at EHFs.[7–11] In one of her early contributions, Stelmachowicz et al[12] developed a high-frequency audiometer prototype, with the intent to measure the age-related decline of EHF hearing. Although there was evidence by that time that EHF thresholds degraded rapidly with age,[8,13] the Stelmachowicz et al[12] study was landmark in that it was one of the first rigorous surveys to provide an accurate comparison of EHF thresholds across the lifespan. Stelmachowicz et al demonstrated that hearing loss at EHFs begins as early as the third decade of life (20–29 years), with losses as great as 20 dB relative to the second decade of life (10–19 years) for frequencies above 14 kHz.

Reinforcing the notion from SII studies that speech frequencies above 6 kHz contributed little to speech perception were additional findings that suggested that amplification of frequencies above approximately 4 kHz failed to improve speech recognition for individuals with hearing loss.[3,14–16] However, one feature common to these studies and SII studies was that they were conducted using adult participants. With her interest in the pediatric population, and perhaps informed by the evidence that children have superior hearing at the higher frequencies, Pat Stelmachowicz began to question whether children might derive benefit from frequencies higher than the traditional speech bandwidth.[17]

In another landmark study on speech bandwidth, Stelmachowicz et al[18] exploited two important facts about speech acoustics: (1) some phonemes, voiceless fricatives in particular, are distinguished by high energy levels > 6 kHz, and (2) different talkers (male vs. female vs. child) have differing spectral characteristics at higher frequencies that could influence the utility of higher frequency bands for speech recognition. Arguing that recognition of the more frequently occurring phonemes like /s/ and their linguistic meaning (e.g., indicating possession or plurality) would be important for both children and adults, Stelmachowicz et al[18] tested the effect of low-pass filtering on speech recognition in quiet for tokens containing voiceless fricatives. Using cutoff frequencies of 2, 3, 4, 5, 6, and 9 kHz (considered full band for that study), they showed that speech recognition scores for a female talker and a child talker reached optimal performance only in the 9-kHz cutoff condition, whereas optimal performance was attained at 5 kHz for the male talker. This talker disparity was particularly striking because most previous studies on speech bandwidth used male talkers.[2,3,5,6]

Armed with these and additional findings, Stelmachowicz et al[19] advocated for increasing the hearing-aid bandwidth for pediatric hearing loss patients and discontinuing the practice of using adult-derived speech bandwidth data to predict children's speech perception. This call was important because it challenged the traditionally defined speech bandwidth, if only for the case of children. Subsequent follow-up studies from the Stelmachowicz lab and her collaborators continued to demonstrate that extended bandwidths beyond 4 to 6 kHz and up to 9 to 11 kHz improved word recognition,[20] nonsense syllable recognition,[20] novel word-learning rates,[21] and word recall for children,[22] particularly for tokens containing voiceless fricatives. Finally, conducting their own SII study using female speech, McCreery and Stelmachowicz[23] demonstrated that nonword recognition in noise for both adults and children was degraded when the 8-kHz octave band (5.6–11 kHz) was filtered out. Their study showed that the importance of the 8-kHz octave band for their speech recognition task was greater than that reported in the ANSI standard.[4]

RECENT WORK ON EXTENDED HIGH FREQUENCIES

It was with this developing backdrop that other groups began to examine the utility of EHFs for speech recognition in noise. Moore et al[24] tested normal-hearing subjects listening to a male target talker spatially separated from two competing male talkers. They found that increasing the bandwidth from 5 to 7.5 kHz provided a small but significant improvement in speech recognition, but increasing from 7.5 to 10 kHz (considered full band for that study) provided no additional improvement. Levy et al[25] similarly tested normal-hearing subjects listening to a male target talker spatially separated from two or four competing male talkers. They found that increasing the bandwidth from 6 to 10 kHz (considered full band for that study) provided a significant improvement in speech recognition.

Around this same time, we demonstrated that listeners are quite sensitive to spectral level changes above 6 kHz in male and female speech.[26,27] Indeed, we would later discover that the average young, normal-hearing listener can detect speech energy above 12.8 kHz for male speech and above 13.1 kHz for female speech.[28] Furthermore, a few studies showed that speech frequencies > 6 kHz in isolation (i.e., speech high-pass filtered at approximately 6 kHz) could provide phonetic information useful for speech recognition.[29–32] Given these findings, it seemed unlikely that information useful for speech recognition would end at 9 to 10 kHz.

In a study by Monson et al,[33] we borrowed a page from the Stelmachowicz approach by again questioning the validity of the traditional speech bandwidth, this time for adults, and asking under what conditions EHFs could be useful for speech perception. Like Stelmachowicz et al,[18] we looked to speech acoustics to exploit another important phenomenon: due to the frequency-dependent directionality of speech radiation from the mouth, EHFs radiate predominantly toward the front of a talker, whereas lower frequencies radiate more omnidirectionally around a talker.[34] This phenomenon means that for a listener in the ecological cocktail party scenario with multiple talkers, EHFs from speech will arrive primarily from a talker facing the listener (presumably the target talker), with little EHF energy masking provided by talkers facing away from the listener (presumably background talkers; see Fig. 1). These circumstances make EHFs optimal for providing speech segregation and phonetic cues in realistic auditory scenes in which talkers naturally have mismatched head orientations.

Monson et al[33] used a testing paradigm that simulated talkers with mismatched head orientations, with a female target talker facing the listener and two competing female talkers facing away from the listener. The selection of female speech was based, in part, on the findings of Stelmachowicz et al[18] that suggested EHFs may be more important for female speech recognition than male speech recognition. We demonstrated a significant improvement in speech recognition for normal-hearing adult listeners when the bandwidth was extended from 8 kHz to full

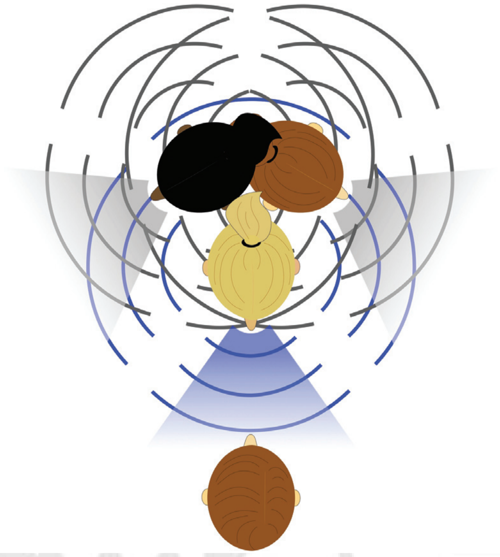

Figure 1 The target (blue) and masker (gray) arrangement simulated in Trine and Monson.[35] Due to the directionality of extended high-frequency radiation (shading) compared to low-frequency radiation (bars), this scenario results in substantial masking at low frequencies, but not at extended high frequencies. Target and masker were presented from a single loudspeaker in front of the listener.

band (22-kHz bandwidth), and later replicated this finding.[35] We subsequently demonstrated the same EHF bandwidth effect, with similar effect size, using our paradigm with normal-hearing children.[36] Motlagh Zadeh et al[37] provided complementary evidence of the utility of EHFs by testing masked female speech recognition for normal-hearing adults. They showed that full-band (20-kHz bandwidth) speech recognition was significantly better when their speech-shaped masking noise was low-pass filtered at 8 kHz than when the full-band noise was used.

Concurrently, several studies have provided evidence that listeners with clinically normal audiograms (up to 8 kHz) but poorer pure-tone thresholds at EHFs have diminished speech-in-noise abilities. Badri et al[38] examined differences present in listeners with clinically normal audiograms who self-reported speech-in-noise difficulties. Although they used female speech materials that contained no EHF energy (8-kHz bandwidth), they showed that listeners who self-reported and exhibited speech-in-noise difficulties on this test had significantly elevated EHF thresholds at 12.5 and 14 kHz compared to the control group. Motlagh Zadeh et al[37] also found group-level differences in self-reported speech-in-noise difficulty, with greater likelihood of reporting difficulty for groups with more severe EHF hearing loss (measured at 10, 12.5, 14, and 16 kHz). They also reported a correlation between EHF pure-tone averages and female-speech-in-noise recognition scores when the speech-shaped noise masker was full-band, although no such relationship was observed when the noise was bandlimited to 8 kHz.

Yeend et al[39] found that EHF pure-tone averages (measured from 9 to 12.5 kHz) for normal-hearing listeners correlated with a speech-in-noise score derived from both self-reported difficulty and two speech-in-noise assessments (male and female speech; 22-kHz bandwidth). Trine and Monson[35] reported correlations between EHF thresholds (measured from 9 to 16 kHz) and female-speech-in-noise recognition using the mismatched head orientation task from Monson et al[33] with young, normal-hearing listeners. Braza et al[40] also used this paradigm with normal-hearing listeners, demonstrating that correlations between EHF thresholds and female-speech-in-noise performance reached significance when the target talker faced the listener while background talkers faced away from the listener, but *not* when target and background talkers were all facing the listener (the traditional testing paradigm). Mishra et al[41] found a relationship between EHF thresholds for normal-hearing listeners (measured at 10, 12.5, 14, and 16 kHz) and male-speech-in-noise recognition using a multi-talker babble masker (11-kHz bandwidth). These findings support a relationship between poor speech-in-noise performance and elevated EHF thresholds.

Although the aforementioned studies indicate potential for EHF audiometry to serve as a diagnostic or predictive tool for speech-in-noise difficulty, others have failed to find a relationship between EHF thresholds and speech-in-noise performance. Liberman et al[42] found no correlation between EHF thresholds (measured from 9 to 16 kHz) and monaural female speech-in-noise (8.8-kHz bandwidth) for normal-hearing listeners. Smith et al[43] also found no relationship between EHF threshold averages (10, 12.5, and 14 kHz) for normal-hearing listeners and speech-in-noise scores using the QuickSIN (female speech; bandwidth unclear). Couth et al[44] likewise found no relationship between EHF threshold averages (12 and 16 kHz) for normal-hearing listeners and spatial-release-from-masking scores using the coordinated response measure (male and female speech; 22-kHz bandwidth). Thus, there are inconsistent findings on the relationship between EHF pure-tone thresholds and speech-in-noise difficulty. This mixed bag of results may emphasize the need for consistent and replicated experimental procedures with high-fidelity speech materials and ecological testing environments.

One question that has arisen is whether the association that has been observed between EHF pure-tone thresholds and speech-in-noise recognition is causal—that loss of audibility of EHF cues in speech degrades speech recognition. Although this effect has been demonstrated using low-pass filtering,[33,35,37] whether elevated EHF thresholds would produce a similar effect is not certain. Another possibility is that EHF thresholds are a marker for subclinical dysfunction at lower frequencies that degrades speech recognition.[41,45] These two possibilities are not mutually exclusive (nor exhaustive[45]) and each could contribute to the observed relationship. One way to assess the latter possibility, however, is to test for an association between EHF pure-tone thresholds and speech-in-noise performance with speech materials low-pass filtered at 8 kHz. Although Liberman et al[42] essentially conducted this analysis and found no relationship, monaural testing over headphones may have influenced their results. In our previous study,[35] we collected data suitable for this analysis using our mismatched head-orientation paradigm. Here we reanalyzed these data, aiming to test whether poorer EHF thresholds predicted young, normal-hearing individuals who performed poorly on speech-in-noise without any available EHF cues.

ADDITIONAL ANALYSIS

Procedure

The methods are described in detail in Trine and Monson,[35] but are repeated here in brief for convenience. Forty-one participants (six males), aged 19 to 25 years (mean = 21.3 years), participated in this experiment. Participants had normal hearing (< 25 dB HL in at least one ear) at standard audiometric frequencies and EHFs of 9, 10, 11.2, 12.5, 14, and 16 kHz. The masker stimulus was a two-female talker babble with both talkers facing 45 degrees or both talkers facing 60 degrees relative to the listener (Fig. 1). Target speech stimuli were the Bamford-Kowal-Bench sentences uttered by a female talker.[46] All recordings were done with 44.1-kHz sampling rate. Stimuli were presented to listeners using a single loudspeaker at 1 m in front of the listener. The level of the two-talker masker was constant, while the level of the target was adaptively varied to estimate the speech reception threshold (SRT), the signal-to-noise ratio required for 50% correct performance. Two masker head orientations were tested (45 or 60 degrees) and two filtering conditions were tested (full band and low-pass filtered at 8 kHz [LP8k]; Fig. 2).

Analysis

In the study by Trine and Monson,[35] we reported an effect of filtering condition and masker head angle on SRTs, and that 16-kHz pure-tone thresholds correlated with SRT in the full-band condition. In the present analysis, we conducted stepwise linear regressions using all audiometric thresholds (standard frequencies and EHFs) to predict SRT scores averaged across masker head angles for the full-band and LP8k conditions. This resulted in 13 possible predictor variables for each model. Separate analyses were conducted using either average left-right thresholds or thresholds for the better ear as predictor variables. Bias can be introduced into stepwise models depending on the entry order of the variables into the model and there is also an increased risk of type I error.[47] To reduce selection bias and to check consistency between stepwise algorithms, stepwise linear regressions were conducted using a combination of forward insertion, backward deletion, and stepwise selection methods.[48] Forward insertion began with an equation with no variables and then with each step, the variable resulting in the lowest Akaike Information Criteria (AIC) was entered,

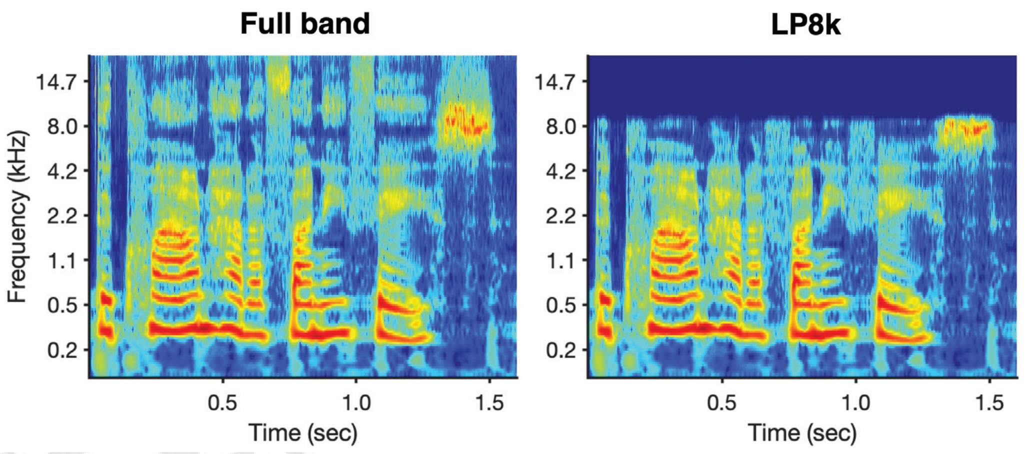

Figure 2 Cochleograms of the female target talker phrase, "The clown had a funny face," showing the effect of low-pass filtering at 8 kHz (LP8k).

until the addition of more variables did not improve the AIC. Backward deletion began with all variables and removed variables until the lowest AIC was achieved. Stepwise selection utilized a combination of both methods. Finally, a linear mixed-effects model was used to examine the influence of subject on performance, with condition as a fixed factor and subject as a random factor. The results of this model were compared against a generalized least squares model to evaluate whether the model improved when subject was included as a random factor. Model fit was assessed by calculating the conditional R^2 (R^2_c for mixed-effects models), which is the proportion of the variance explained by both fixed and random effects.[49] Statistical analyses were conducted using the step, lme, gls, and rsquared functions in R (R Core Team, 2020).

Results

Examination of histograms of scores on all variables revealed approximately normal distributions with no extreme univariate or bivariate outliers detected. Q-Q plots revealed approximately normal distributions and Shapiro–Wilk test was nonsignificant (p >0.05). Univariate Pearson's correlation showed a significant positive correlation between the full-band SRTs (averaged across masker head angles) and left-right-averaged pure-tone thresholds ($R = 0.34$, $p = 0.03$; Fig. 3). Results were not significant using better ear pure-tone thresholds ($R = 0.30$, $p = 0.06$).

We first report the stepwise models testing full-band performance. For each selection method using left-right averaged pure-tone thresholds, the final model (Model 1) was the same, which included 3 of the 13 predictors (8, 12.5, and 16 kHz) and was statistically significant ($R^2 = 0.27$, adjusted $R^2 = 0.21$, F (3, 37) = 4.48, $p = 0.008$). For each selection method using better ear pure-tone thresholds, the final model (Model 2) was also the same, which included 3 of the 13 predictors (8, 12.5, and 16 kHz) and was statistically significant ($R^2 = 0.29$, adjusted $R^2 = 0.24$, F (3, 37) = 5.1, $p = 0.005$). The coefficients and significance values for each predictor variable for these models are included in Tables 1 and 2.

For stepwise models testing LP8k performance, each selection method using left-right averaged pure-tone thresholds resulted in the same final model (Model 3), which included 3 of the 13 predictors (1, 8, and 16 kHz) and was statistically significant ($R^2 = 0.37$, adjusted $R^2 = 0.32$, F (3, 37) = 7.39, p <0.001). Each selection method using better ear pure-tone thresholds resulted in the same final model (Model 4), which included 3 of the 13 predictors (8, 12.5, and 16 kHz) and was statistically significant ($R^2 = 0.38$, adjusted $R^2 = 0.33$, F (3, 37) = 7.68, p <0.001). The coefficients and significance values for each predictor variable for these models are included in Tables 3 and 4.

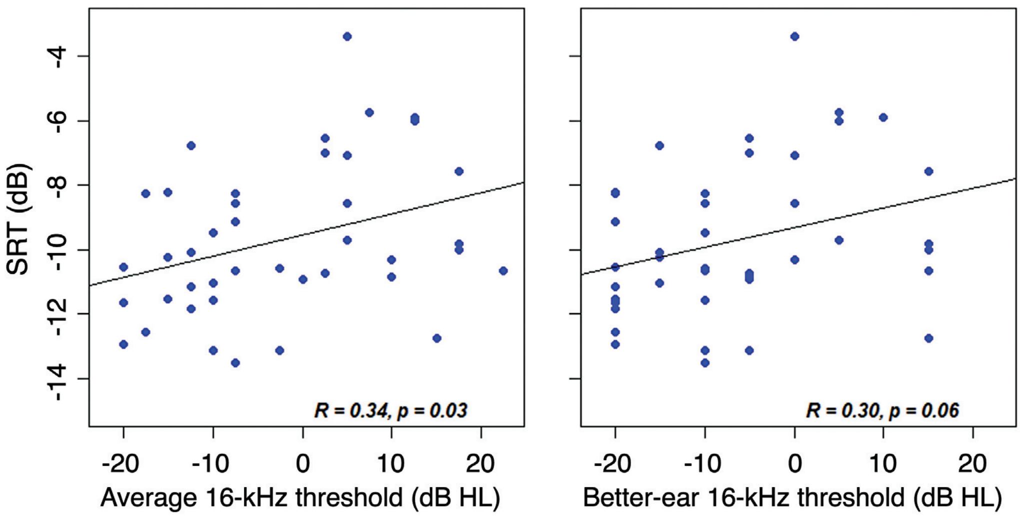

Figure 3 Mean SRTs for the full-band condition plotted against the left-right averaged 16-kHz pure-tone threshold (left panel) or better ear 16-kHz pure-tone threshold (right panel).

Table 1 Coefficients and significance values for Model 1 resulting from left-right averaged (AVG) thresholds as predictor variables for the full-band condition

	Estimate	*p*-Value
(Intercept)	−9.19	<0.001
AVG 8 kHz	−0.13	0.054
AVG 12.5 kHz	0.16	0.014
AVG 16 kHz	0.06	0.039

Table 2 Coefficients and significance values for Model 2 resulting from better ear (BE) thresholds as predictor variables for the full-band condition

	Estimate	*p*-Value
(Intercept)	−8.72	<0.001
BE 8 kHz	−0.15	0.016
BE 12.5 kHz	0.15	0.011
BE 16 kHz	0.09	0.008

Table 3 Coefficients and significance values for Model 3 resulting from left-right averaged (AVG) thresholds as predictor variables for the LP8k condition

	Estimate	*p*-Value
(Intercept)	−7.13	<0.001
AVG 1 kHz	0.15	0.105
AVG 8 kHz	−0.22	0.003
AVG 16 kHz	0.13	<0.001

Table 4 Coefficients and significance values for Model 4 resulting from better ear (BE) thresholds as predictor variables for the LP8k condition

	Estimate	*p*-Value
(Intercept)	−7.03	<0.001
BE 8 kHz	−0.22	0.002
BE 12.5 kHz	0.10	0.105
BE 16 kHz	0.14	<0.001

A linear mixed-effects model predicting SRTs with filtering condition as a fixed factor and subject as a random factor was compared against a generalized least squares linear model that did not include effects of subject. The mixed-effects model had a lower AIC than the least squares model (1,090 vs. 1,215, respectively) and an ANOVA revealed a statistically significant difference between the two models ($p < 0.001$). Thus, the model prediction improved when subject was included as a random factor (mixed-effects model $R^2_c = 0.61$).

DISCUSSION

From the current body of work on the contribution of high-frequency and EHF bands to speech recognition, it seems clear that it is time to retire the notion of a limited speech bandwidth for speech perception for both children and adults. It is also clear that Pat Stelmachowicz helped prepare the ground for such an idea to take root. Her research on speech bandwidth with female talkers and child listeners was instrumental in revealing the limitations of the prior speech bandwidth work. Those of us currently working in this area owe her a debt of gratitude for her persistence in pushing the boundary—or in this case, the bandwidth—of speech perception research.

Similarly, Stelmachowicz's study on EHF hearing across the lifespan stands as an often-cited reference when ascertaining the utility of EHF audiometry for children and adults. At present, EHF audiometry is used clinically to detect, for example, early signs of ototoxicity or premature hearing loss for some at-risk populations.[45] A growing number of studies and the data we have presented here also suggest that EHF audiometry could be used more broadly as a diagnostic tool for individuals at risk for speech-in-noise difficulties. In our present analysis, the 8- and 16-kHz pure-tone thresholds were consistently selected in all four models to predict speech-in-noise recognition. This finding is even more striking when considering that our participants were all young, normal-hearing listeners with good EHF thresholds (<25 dB HL).

Importantly, our finding that only one lower frequency (1 kHz) was selected for only one model suggests that EHF thresholds are more indicative of speech-in-noise performance than conventionally measured thresholds, at least for individuals without hearing loss. That EHF thresholds predicted SRTs for the LP8k condition, when EHF cues in speech were unavailable, suggests elevated EHF thresholds may flag underlying auditory pathologies impeding speech recognition in noise, providing valuable diagnostic information for a clinician. One caveat to this interpretation is that, while better 16-kHz thresholds predicted better speech in noise in our analysis, *poorer* 8-kHz thresholds were associated with better speech in noise. This finding indicates there may be a complex relationship between EHFs and standard audiometric frequencies that is yet to be resolved.

There is a substantial adult patient population who present with clinically normal hearing and report speech-in-noise difficulties. Our finding of an effect of subject across filtering conditions reinforces the notion that some normal-hearing individuals consistently have greater difficulty with speech-in-noise. In some cases, these difficulties can be attributed to impaired central auditory processing, auditory neuropathy, cochlear synaptopathy, or other lesions to the auditory system.[50] However, there remains a subset of individuals who are offered limited or no treatment options, continue to experience difficulty, and, in the end, are dissatisfied with their appointments.[51] By including EHF thresholds as part of a routine test battery, it may be possible to offer an evidence-based clinical explanation for their difficulties, which can be more satisfactory for patients and a step toward establishing a stronger clinician–patient relationship.[52]

In conclusion, we wish to pay tribute to Pat Stelmachowicz and the substantial body of work with her name attached to it. Improving our understanding of speech bandwidth and EHF audiometry represents only two of the many research areas where her influence has been profound. It is hoped that future work can continue to honor her efforts by illuminating the utility of EHFs for speech perception for children and adults.

CONFLICT OF INTEREST

None declared.

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