Extended High Frequency in Hearing and Speech[1]

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Elephants to Bats and the Range of Human Hearing

The audible frequency range specific to humans, known as the human hearing range, can extend from 20 Hz to 20 kHz depending on how good a person's hearing sensitivity is at higher frequencies. Yet, the understanding of human hearing capabilities has been limited to an upper limit of about 8 kHz because the primary explorations of these capabilities have historically been in the context of speech communication. After all, humans speak to be understood, and they need to hear well to perceive the sounds of speech.

Indeed, hearing loss is associated with difficulty understanding speech, and the standard clinical measurement of hearing is limited to tone sensitivity up to 8 kHz. Thus, does the human hearing range above 8 kHz have limited utility because it is unnecessary for speech communication? What is the advantage of having extended hearing up to 20 kHz? To better understand these issues, this article discusses recent research in speech and hearing and explores the potential of extended high-frequency hearing and the availability of high-frequency speech information in the audible range of human hearing.

Before we delve into issues related to human speech and hearing, let us pause and reflect on the audible frequency ranges in mammalian hearing because high- and low-frequency sensitivity is common to both humans and animals, irrespective of species-specific frequency limits. When interacting with animals, humans can easily hear cats and dogs because their vocalizations fall within the human hearing range, but humans may not be aware that the upper limit of hearing in these (and most other mammals) is much higher than theirs (Fay, 1994). To compare human and animal hearing, the hearing range is typically defined as the ability to detect sounds 50% of the time at the intensity level of 60 dB of sound pressure level (SPL) (Heffner and Heffner, 2007). Using this criterion, many mammals have better high-frequency hearing than humans, with the upper limit of about 45 kHz for dogs, about 80 kHz for cats, and about 85 kHz for the domestic house mouse.

High-frequency hearing in other mammals can even be higher. Bats are the most famous example, reaching or exceeding 200 kHz (Davies et al., 2013). The nonhuman mammalian ability to hear sounds at frequencies higher than humans is referred to as ultrasonic hearing (i.e., hearing high-frequency sounds inaudible to humans). Conversely, hearing sounds at frequencies below the lower limit of the human range is called infrasonic hearing (**Figure 1**). We note that what constitutes ultrasonic and infrasonic hearing is anthropocentric.

A hallmark example of infrasonic hearing is the low-frequency sensitivity of the elephant, reaching 16 Hz at 65 dB and 17 Hz at 60 dB SPL (Heffner and Heffner, 1982). In general, an elephant has good low-frequency hearing but poor high-frequency hearing (unable to hear sounds above 12 kHz). Indeed, research has established that mammals with good high-frequency hearing have poor low-frequency hearing (and vice versa), and the mammalian limit of low-frequency hearing varies directly with the high-frequency limit (Jackson et al., 1999). These variations are species specific.

The best human hearing sensitivity is from 2 to 4 kHz. In the 2- to 4-kHz range, humans can hear very soft sounds;

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[1] *For additional information on extended high frequency, see the upcoming special issue of* The Journal of the Acoustical Society of America *on "Perception and Production of Sounds in the High-Frequency Range of Human Speech."*

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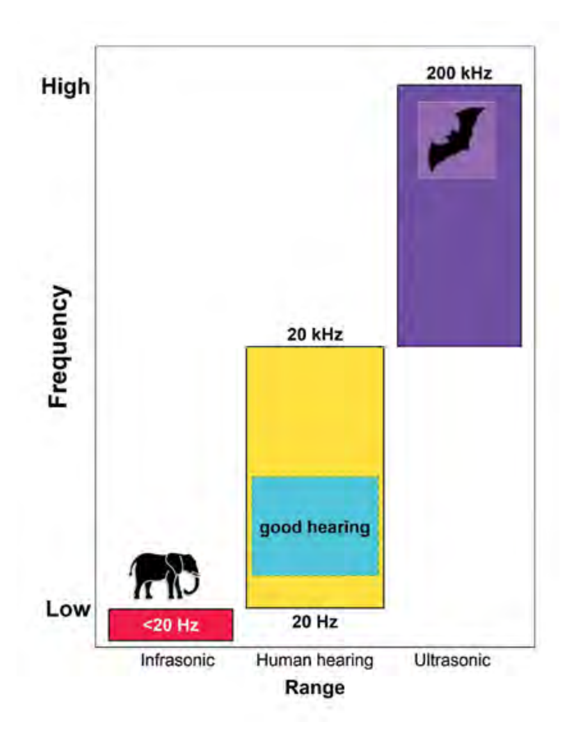


Figure 1. *A schematic illustrating species-specific good high- and low-frequency hearing relative to the human hearing range.* ***Left:*** *good hearing in elephants is in the infrasonic range of human hearing, below 20 Hz, but their high-frequency hearing also overlaps with humans, up to 12 kHz (not shown).* ***Center:*** *the audible frequency range for some humans is from 20 Hz to 20 kHz, but the good hearing range (i.e., good hearing sensitivity) is from about 250 Hz to 8 kHz.* ***Right:*** *bats have good hearing in the ultrasonic range (can hear sounds higher than humans), although their low-frequency hearing overlaps with the upper frequencies of the human range (not shown).*

pure tones can be audible at a level of –10 dB SPL (Jackson et al., 1999). Extending this highest sensitivity range, human hearing is still very good from 250 Hz to 2 kHz and 4 kHz to 8 kHz, with pure tones being audible at 10 dB SPL. However, sensitivity drops below 250 Hz and above 8 kHz, and sounds must be much louder to be perceivable, even by individuals with uncompromised hearing. Using the 60 dB SPL criterion in comparing the ranges of human and animal hearing, the human range can extend from 31 Hz to 17.6 kHz. Above 17.6 kHz, sounds can still be audible for some, but they need to be even more intense. In Jackson et al. (1999), only 3 of 6 adult listeners could hear 20-kHz pure tones at 91 dB SPL. Thus, compared with the hearing ranges of most high-frequency hearing mammals, human hearing sensitivity places humans as having good low-frequency hearing but relatively poor high-frequency hearing.

However, even if human hearing sensitivity at higher frequencies may not be as good as it is in the 250-Hz to 8-kHz range, humans can hear moderately intense signals, such as those produced in a normal conversation, at higher frequencies. Unfortunately, knowledge of how humans may utilize high-frequency information in speech communication is severely limited. This article discusses the historical reasons for the lack of interest in exploring the potential of high-frequency information for communication purposes and considers several areas of recent research that collectively make a case for a more important role of high frequency in hearing and speech than previously thought.

Can You Hear Me Now? The Range of Telephones, Then and Now

Because hearing in humans is very good in the 250-Hz to 8-kHz range, how much high-frequency information is needed for successful speech communication? When humans hear someone speaking, they listen for comprehension, attending to words and phrases to understand the overall message. Early research at Bell Telephone Laboratories, Murray Hill, New Jersey (e.g., French and Steinberg, 1947) established that acoustic energy from 250 Hz to 4 kHz is essential to speech intelligibility because it contains most cues to vowels and consonants. This work also established 7 kHz as the upper frequency limit contributing significantly to spoken language comprehension.

The focus of this early work was both theoretical and practical because theoretical models were needed to improve telecommunication devices. Consequently, the finding that intelligibility does not suffer when the speech spectrum above 4 kHz is experimentally removed led to the general acceptance of the "telephone bandwidth" in traditional narrowband telephony.

Remember the old phones from the precellular times? They transmitted voice using a narrow bandwidth between 0.3 and 3.4 kHz and it worked! This bandwidth still preserved those speech characteristics considered necessary and sufficient for successful communication, to talk on the phone or make public announcements over loudspeakers. Listen to a sentence low-pass filtered at 4 kHz, approximating the narrowband telephone bandwidth (see **Multimedia File 1** at acousticstoday.org/JacewiczMedia). As you may have found, the sentence "I work for the school system" is fully intelligible despite the loss of acoustic energy above 4 kHz.

In recent years, however, audio media technologies (e.g., videoconferencing, voice of internet protocol, or cellular telephony) have steadily moved toward wideband or high-definition (HD) audio, with the upper frequency band extended to 7 kHz. This wideband audio coding not only improves voice quality, but the additional high-frequency information provided for specific speech sounds such as "s" can disambiguate words such as "thick" and "sick."

Indeed, this wideband audio meets today's needs and is now considered sufficient for telecommunication purposes. Listen to the same sentence low-pass filtered at 7 kHz and notice how the sound quality has improved (see **Multimedia File 2** at acousticstoday.org/JacewiczMedia). The advantage of increasing the frequency limit to 7 kHz is not as much in improved speech intelligibility but in reduced listening effort in processing the "s" sounds. Impressionistically, the words sound "crispier" (particularly the last word, "system"), and the message conveyed is easier to follow. The wider frequency bandwidth may be particularly useful in processing the sounds of foreign names or unfamiliar terminology.

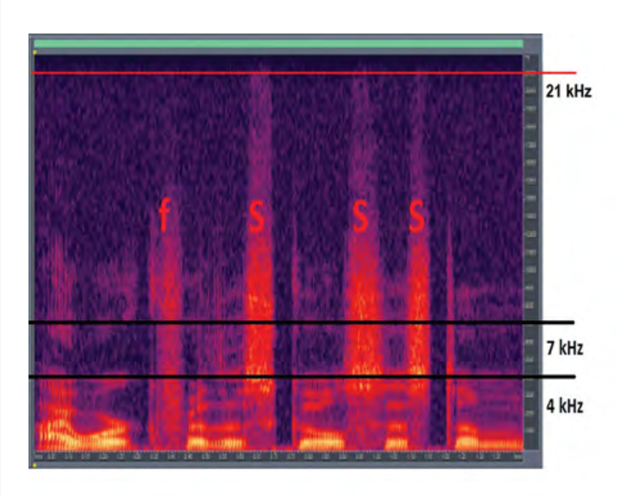
Based on the foundational research at Bell Telephone Laboratories (e.g., Fletcher and Galt, 1950) and many subsequent studies, the frequency range past 7 kHz is not expected to further improve speech intelligibility. Listen to the same sentence that has not been modified (see **Multimedia File 3** at acousticstoday.org/JacewiczMedia). The sentence was recorded at a 44.1-kHz sampling rate, the standard rate for audio CDs, and contains frequency information up to the limit of human hearing at 20 kHz. You probably do not notice any difference between examples 2 and 3. This is because even if some spectral information is missing, listeners can use a form of top-down (or "big picture") processing based on their prior knowledge and experience with pronunciation variability across different speakers to mentally "fill in" predictable information.

Pushing the Limit: Extended High-Frequency Speech Sounds

If unnecessary and more than sufficient, can the upper-frequency range above 7 kHz, the extended high-frequencies, still be useful for speech perception or increase our understanding of speech acoustics? Consider how much spectral energy is still available between 7 kHz and 20 kHz in the spectrogram of our unmodified sentence "I work for the school system" (**Figure 2**). The four consecutive noise bars represent "noisy" consonants called fricatives, emphasized here in red for illustration purposes: I work *f*or the *s*chool *sys*tem. Fricatives are classified as high-frequency sounds because their spectral energy peaks are in the high-frequency range (near or above 8 kHz for some sounds).

Figure 3 shows the average spectrum of the fricative "s" in words produced by a female talker (Alexander, 2019). As shown, a significant amount of extended high-frequency energy for "s" is produced by adult females; the average

Figure 2. *A spectrogram of the sentence "I work for the school system" recorded by a male talker. The sentence has energy up to at least 21 kHz. The low-frequency band marked at 4 kHz has been considered "necessary" to understand speech, and it approximates the 0.3- to 3.4-kHz bandwidth in traditional narrowband telephony. The higher band marked at 7 kHz is currently considered "sufficient" to understand speech in modern telecommunication devices. Note how much spectral energy is still available above 7 kHz, especially in fricatives "s" and "f."*



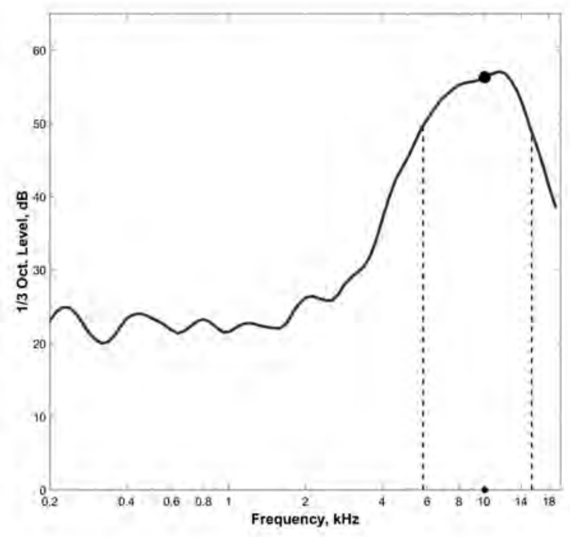


Figure 3. *Composite spectrum of the "s" sound extracted from 66 words spoken by a female talker.* ***Closed circles:*** *mean of the peak frequency.* ***Dotted lines:*** *means of the lower and upper shoulder frequencies (10 dB down from the peak).*

peak frequency of the "s" in this talker's words exceeds 10 kHz. As a rough estimate of the usable bandwidth for perception, the lower and upper shoulder frequencies, 10 dB down from the peak, are shown **Figure 3**, *dotted lines*. For this talker, the mean frequency of the high-frequency shoulder of "s" is 15.4 kHz.

The spectrum shown in **Figure 3** is a typical case because the range of values for the peak and upper shoulder frequencies across six female talkers was within an approximately one-third octave (Alexander, 2019). Although the peak frequency across the talkers, with a mean of 9.4 kHz and a range of 7.9-10.6 kHz, are consistent with previous reports, the frequencies of the upper shoulder are remarkably high, with a mean of 13.7 kHz, a range of 12.2-15.4 kHz, and a handful of reproductions exceeding 18 kHz. Although it is not a new finding (e.g., Tabain, 1998), the extent of high-frequency energy in "s" produced by female talkers has not been frequently reported. This is likely because the digital sampling rates used by many previous studies limited the amount of energy above 11 kHz.

The acoustic characteristics of "s" and other fricatives have been studied systematically since the early 1960s (e.g., Strevens, 1960). However, interest in frictives has intensified in speech research over the last three decades because modern computers offer greater computational possibilities. In the case of fricatives, a significant technological advancement was that speech recordings could be sampled at higher rates (44.1 kHz or even 48 kHz), which allowed for the development of new acoustic measures of fricatives that included spectral information up to 20 kHz. Even in the early 2000s, fricatives were recorded at the then-standard 22.05-kHz rate and their spectral content could only be analyzed up to 11 kHz. The seminal comprehensive acoustic analysis of English fricatives by Jongman et al. (2000) is a fitting example of this approach.

What have we learned from analyzing the acoustic spectra of fricatives in the entire range of human hearing, up to 20 kHz? More detailed measures characterizing fricatives have been proposed, with parameters defined specifically for use with sampling rates of 32 kHz or higher (Shadle, 2023). Indeed, using modern analytics, large corpora of speech, and machine-learning approaches, studies compared the effectiveness of various fricative measures (e.g., Kharlamov et al., 2023) or acoustic variation in individual speaker's pronunciation (Ulrich et al., 2023).

Investigating children's speech, full-spectrum-based measures uncovered significant acoustic differences between the pronunciation of fricatives in children with typical and distorted pronunciation (Miodonska et al., 2022). Children who were born deaf and were later fitted with cochlear implants (CIs) were found to pronounce fricatives differently from children with normal hearing (Yang and Li, 2023); this is because CI devices typically cover the speech spectrum only up to 8 kHz (Svirsky, 2017), making learning the fine-grained distinctions in the high-frequency sounds challenging for CI users.

Extended High-Frequencies Benefit Perception

Having established that there is sufficient speech energy in the extended high-frequency region for people with good hearing to detect, the question remains whether they can use this information to help comprehend speech. To address this question, we first highlight pathological and experimental cases where the high and extended-high-frequency bands almost exclusively transmit the speech signal. Then, we discuss the ways information in the extended high frequencies can benefit people in everyday listening situations.

That's Incredible!

Although most cases of sensorineural hearing loss have the earliest and most severe impact on the high-frequency range of hearing, there is a small subgroup of individuals with the opposite pattern of hearing loss: little-to-no usable hearing through 8 kHz with normal-to-mild hearing loss in the extended high-frequencies. In the mid-1970s, Charles Berlin was introduced to a young adult with significant hearing loss in the classic "speech frequencies," with normal thresholds in the extended high-frequency region.

Before being diagnosed by Berlin, this individual's audiological record baffled doctors and clinicians. For the previous 10 years, the only explanation was hysteria, so she was consequently treated with psychiatric and psychological care (Berlin et al., 1978). The dilemma was that she could detect speech at levels 50 dB lower than would be predicted by her detection thresholds for pure tones through 8 kHz, which were in the severe-to-profound range. In addition, she had nearly "perfect" pronunciation of the fricatives and "superb lip-reading ability" (Berlin, 1985). She could also respond to very soft, high-frequency sounds, such as when being called from another room (Berlin, 1985).

Berlin's previous work on ultrasonic hearing in animals led him to question her extended high-frequency hearing; however, the limits of human hearing in this range were not well-known at the time. Therefore, he had to improvise with what he could find; he started by modifying his ultrasonic transducer for animal testing to measure her hearing (Berlin et al., 1978). His work was so pioneering that normative threshold values in the extended high-frequency range had to first be developed only after finding a suitable audiometer with a low signal-to-noise ratio in this range. Ultimately, Berlin discovered that she had normal thresholds for frequencies at 12 kHz and higher, which could explain her anomalous communication abilities. Therefore, he commissioned an upward frequency-shifting hearing aid for her that transposed low-frequency sounds up to 12 kHz, which she successfully used for decades (Berlin, 1982). Her hearing loss and success with Berlin's device earned her a story in *Time* Magazine (1982) and a cameo on the popular 1980s TV show *That's Incredible!*

Perhaps Not So Incredible But Ordinary

Although Berlin's star patient, one of the dozens of patients he later reported on, had an unusual pattern of hearing loss, her ability to exploit speech information from the extended high-frequency range in the face of sparse information from the typical speech frequency range is not. Under experimental conditions with severe signal degradation, individuals with normal thresholds throughout most of the range of human hearing have also been shown to harness extended high-frequency acoustic energy to support speech understanding.

Using normal-hearing subjects, Lippman (1996) tested the perception of nonsense syllables spoken by a female talker. The recordings were band-stop filtered, so the only acoustic energy was below 0.8 kHz and above a variable high-frequency cutoff between 3.15 and 10 kHz. Results indicated that speech recognition was 44% with just the low-frequency band but improved to almost 90% when combined with information from the high-frequency band above 4 kHz. Speech recognition remained relatively high at 74% when the high-frequency band was above 8 kHz; recognition of "s" in this condition was 100%. Recognition for several other consonants remained high when the high-frequency filter cutoffs were set at 8 and 10 kHz. These findings suggest that normal-hearing individuals can accurately perceive many speech sounds without midfrequency cues by combining information from the high-frequency speech spectrum with a limited range of information from the low-frequency speech spectrum.

Spatial Hearing

Besides detecting and recognizing specific speech sounds in experimentally narrow conditions, how else do humans use information from the extended high-frequency range? The extended high-frequency spectrum can enhance spatial hearing by helping people and animals to localize sound sources. This is because high-frequency sounds have shorter wavelengths than low-frequency sounds. Shorter wavelengths are more directional, so they are more easily affected by the shape of the outer ear, the head, and the surrounding environment, making it easier to determine the location of a sound source. One classic example is the head shadow effect, whereby high-frequency sounds originating from the left or right are reflected off the head and cast a sound shadow on the opposite side. For example, if you are standing in a room and someone is talking to you from the left, the high-frequency sounds in their voice will be louder in the left ear compared with the right ear. The difference in loudness between the two ears will depend on the talker's location. The auditory system can use these loudness differences to help determine the direction of the sound source.

The extended high-frequency spectrum also provides critical cues for the localization of sounds varying in elevation since auditory comparisons of the sound arriving at the two ears are ineffective because each ear receives the same information. Instead, cues for localizing sound in the vertical dimension depend heavily on the diffraction of sound around the small folds and ridges of the outer ear (Middlebrooks and Green, 1991). Because the diffraction of sound waves is only significant when the object or opening is about the same size as the wavelength of the sound wave, the high and extended high frequencies carry the most relevant information about the elevation of sound sources (Hebrank and Wright, 1974).

Speech Perception in Challenging Conditions

Most clinical and laboratory tests of speech perception do not reflect real-world communication environments. For example, talkers are limited in number and dialectal variability and are recorded in sound-treated rooms. In addition, recording methods such as the sampling rate, microphone style, and microphone position are not ideally suited to capture the extended high-frequency spectrum. Furthermore, when multiple talkers are combined or presented to the listener, they are often mixed in a single channel and/or played from a single loudspeaker.

These elements diminish the estimated contributions of extended high-frequency hearing in our everyday lives, particularly in challenging communication situations. Communication challenges can come from various sources, including background noise, reverberation, competing talkers, and language/cultural differences. These challenges reduce the redundancy of a talker's message as provided by contextual cues and predictability at every linguistic level (e.g., coarticulation of speech sounds to higher level information at the sentence and talker level). In general, the less predictable and contextually rich the spoken message is, the more extended high-frequency information will contribute to its understanding. This occurs because signal degradations often more adversely affect the lower frequency cues that significantly contribute to top-down processing, hence the ability of the listener to compensate for missing information in the acoustic signal.

Listening to speech in the presence of other competing talkers is one of the most challenging listening conditions, in part because the target (talker of interest) and maskers (other talkers) are more likely to share similar spectral and temporal characteristics compared with other masker sources (e.g., the sound of a fan or a backup warning beep on a truck). These commonalities can make it difficult to hear the target (energetic masking) and segregate the talker from the others (informational masking).

Monson and colleagues (Trine and Monson, 2020; Monson et al., 2023) demonstrated that the extended high-frequency spectrum contributes more to speech perception in these conditions than previously thought. They identified limitations of most experimental methods involving multiple talkers. One major limitation is that talkers are often recorded with the microphone directly in front of the mouth, which assumes that all the talkers face the listener and directly speak to them. Another limitation is that multiple talkers are often presented to the listener from a single loudspeaker in the front, similar to the talkers being in precisely the same position when speaking.

Although seemingly benign, these methodological details neutralize the differences in the extended high-frequency spectrum between the target and maskers (Trine and Monson, 2020; Monson et al., 2023). When a talker (target) speaks to someone, they usually face them, allowing the short wavelengths of the extended high-frequency speech to reach the listener's ear. However, other talkers (maskers) in the same environment are likely to be speaking to someone other than the listener, so they will face slightly off angle from the listener, even if they are in front of them. Thus, the extended high-frequency speech from the maskers will be reduced when it reaches the listener's ears, thereby boosting the signal-to-noise ratio in this region.

Monson et al. (2023) suggest that this release from energetic masking in the extended high-frequency region can increase the understanding of the talker facing the listener in ordinary conditions by providing additional access to the cues for vowels and consonants, including those not typically associated with the extended high-frequency spectrum. Additionally, increased access to the extended high-frequency spectrum can promote segregation and selective listening of the talker facing the listener by exploiting the synchronized pattern of amplitude changes across the entire spectrum.

Future Directions

To what extent high-frequency energy in speech sounds can improve real-world speech communication is still unknown. Although laboratory experiments show that certain acoustic cues can be useful in perception, it is also the case that listeners adapt to contextual variation in speech and compensate for a loss of specific acoustic cues. More work is needed to better understand the perceptual importance of high-frequency energy in noisy sounds such as fricatives. It has been recently proposed that "human auditory system features, including the upper limit of hearing, have developed because of their ecological utility for detection and processing of speech" (Hunter et al., 2020, p. 3). Investigations using languages with a much richer inventory of high-frequency sounds than English (e.g., Mandarin, Polish, Russian, Greek, or Dravidian languages spoken in parts of India, Sri Lanka, and Pakistan) would be particularly insightful in providing evidence that hearing the fine-grained acoustic distinctions when learning a language is key to articulatory precision in producing them.

Speaker characteristics (not only vowels and consonants) are integral to human speech. When processing spoken language, we not only listen to what is being said but also who is talking. Perception studies have shown that high-frequency energy provides information about a speaker's gender (male or female), even in the absence of low-frequency cues. The primary cues to voice gender are in the low-frequency range, up to about 3 kHz, including the voice's fundamental frequency and the lower vowel formants. However, listeners can identify gender accurately even when speech is high-pass filtered at 5-12 kHz and the low-frequency content is removed (Donai and Halbritter, 2017). Moreover, they can identify gender only from brief vowel segments high-pass filtered up to 8.5 kHz. Similar results for gender identification have been reported in several other studies, which further underscores the usefulness of high-frequency information in speaker recognition (see Monson et al., 2014, for a comprehensive review). More recent research added that gender cues in the high-frequency range are almost as strong as in the low-frequency range, and information about a speaker's regional dialect is available in the 6- to 11-kHz range despite intelligibility loss (Jacewicz et al., 2023). Whether information about other speaker characteristics, physical, psychological, and social, is retained at the high end of the speech spectrum is still unknown, and future work is needed to explore this possibility.

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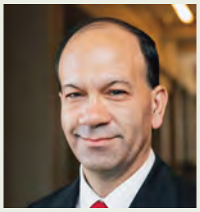

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