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Strategies for Maximizing Speech-Recognition Performance: Adults With Mild to Moderately Severe Sensorineural Hearing Loss

Jeremy J. Donai, AuD, PhD
and
Jeremy C. Schwartz, BS
West Virginia University
Morgantown, WV

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Structured Abstract

Clinical Question: What high-frequency amplification strategy maximizes speech-recognition performance among adult hearing-impaired listeners with mild sloping to moderately severe sensorineural hearing loss?

Method: Quick response review

Study Sources: EBSCO, PubMed, Google Scholar, as well as journals from the American Speech-Language-Hearing Association (ASHA) and American Academy of Audiology (AAA)

Search Terms: The following terms were used in isolation and in several different combinations: mild to moderately severe, high-frequency, hearing loss, amplification, frequency lowering, and extended bandwidth.

Number of Included Studies: 18

Primary Results:

Increased access to high-frequency speech energy enhances speech-recognition performance in noise for hearing-impaired listeners.

Certain frequency-lowering techniques have no effect or significantly reduce speech recognition in noise for hearing-impaired listeners.

There is less evidence to support amplifying the high-frequency region of speech in quiet listening conditions.

Conclusions:
There is a significant need for randomized controlled studies of the amplification techniques under examination in this Brief. These studies should make direct comparisons of speech-recognition outcomes in quiet and noise between various techniques using clinically available hearing aids. The outcomes of such studies should help elucidate the most efficacious means of amplifying high-frequency speech energy and should inform clinical decision making for hearing healthcare professionals.

Strategies for Maximizing Speech-Recognition Performance: Adults With Mild to Moderately Severe Sensorineural Hearing Loss

Jeremy J. Donai
Jeremy C. Schwartz

Clinical Scenario

John is early in his first year as a practicing audiologist and is currently working in a private-practice setting. During the previous 3 months he has attended educational trainings provided by various hearing aid manufacturers. During some of these trainings, the presenter was persuasive in recommending frequency-lowering technology (i.e., technology that lowers information from the high-frequency region to a lower-frequency region) for amplifying high-frequency sensorineural hearing loss. In other sessions, however, extended-bandwidth amplification (i.e., amplification with a wide spectral bandwidth out to approximately 8–10 kHz) was recommended as the standard of care for providing audibility of high-frequency information.

John is conducting a hearing aid evaluation on Mr. Smith, a 50-year-old patient who has a bilateral, mild sloping to moderately severe sensorineural hearing loss (SNHL). Mr. Smith's otologic history is unremarkable and he has never used amplification. Mr. Smith reported recently experiencing a mild cerebrovascular accident (CVA) and is scheduled to begin speech-language therapy next week to address mild speech-production difficulties. Thus, one of John's goals is to maximize Mr. Smith's speech-recognition abilities to ease communication and facilitate maximum audibility of the speech signal during the therapy sessions. John does not yet know which amplification strategy to use to maximize speech recognition for Mr. Smith and has decided to conduct a review of the literature to help guide his decision.

Background Information

Currently, there is a lack of agreement regarding the best way to provide audibility of high-frequency speech information through amplification devices, particularly for individuals like Mr. Smith who have moderate to moderately severe high-frequency thresholds. Some propose extending the spectral bandwidth of amplification (i.e., including additional high-frequency information) to improve speech-recognition performance. Others, conversely, recommend moving speech information from the high-frequency region to lower-frequency regions through various signal-processing techniques (for specific details see Alexander, 2013). Interest in these signal-processing techniques resulted from the potential limitations of traditional amplification for high-frequency hearing loss (Alexander, 2013). For example, prior to widespread use of digital feedback-suppression algorithms in amplification devices, providing gain in the high-frequency region was a significant clinical challenge.

The literature is clear on the fact that providing access to and audibility of the high-frequency region of the speech signal is beneficial for listeners of all ages (Füllgrabe, Baer, Stone, & Moore, 2010; Monson, Hunter, Lotto, & Story, 2014; Pittman, 2008; Stelmachowicz, Lewis, Choi, & Hoover, 2007). For example, Pittman (2008) found improvements in novel word learning among children with normal hearing and children with hearing impairment when making more high-frequency information audible (i.e., extending the speech-signal bandwidth). For adults, Moore, Füllgrabe, and Stone (2010) found that including additional high-frequency speech energy (above 5 kHz) increased listener judgments of sound quality, with signals containing energy up to 10 kHz described as having improved "clarity" and "pleasantness." The authors also found a small, but significant, improvement in speech recognition when extending the spectral bandwidth (i.e., including additional high-frequency energy) to 7.5 kHz when the speech signal and noise were presented from different locations.

Clinical audiologists should strive to provide appropriate amplification that maximizes speech understanding and sound quality in all listening environments. Similarly, speech-language pathologists should understand the effectiveness and outcomes associated with amplification systems for patients with hearing loss.

Clinical Question

John undertook the current review to explore the literature on the two approaches to improving speech recognition for patients with hearing loss. John used the PICO (population, intervention, comparison, outcome) format, as recommended by the American Speech-Language-Hearing Association (AHSA), to formulate his clinical question: For adults with mild sloping to moderately severe SNHL (P), is frequency-lowering processing (I) or extended-bandwidth processing (C) preferable in improving speech recognition performance (O) in quiet and noisy listening environments?

Search for the Evidence

Because John had less than a week to provide a solution to Mr. Smith, he used the Quick Review Response (QRR) method described by Larsen and Nye (2010). According to the authors, this technique expedites information retrieval, data extraction, and analysis to provide preliminary answers to questions using methods commonly used in a full systematic review. Limitations of this method include: 1) sources of information retrieval may be limited, and 2) data analysis focuses solely on primary outcomes and ignores moderating variables that would allow for a deeper understanding of the outcomes (Larsen & Nye, 2010). Given the time constraints, John deemed this technique appropriate for the clinical decision at hand.

Inclusion Criteria

The primary criterion for inclusion in the analysis was peer review. John was aware that this criterion would exclude white papers written by hearing aid manufacturers, research articles from trade journals, and unpublished doctoral dissertations. Since the patient was an adult male, articles referencing work specifically with children in the title or abstract were excluded. The dependent variable was limited to some form of speech identification (e.g., phonemes, words, sentences) and not to the detection of specific phonemes/morphemes (e.g., detection of the presence or absence of signals from the fricative class of phonemes as in the Plurals Test). John limited the dependent variable to examine the effects of various audible bandwidths and signal-processing techniques on the linguistic processing of the speech signal rather than simply phonemic detectability. For the purposes of this review, the term *extended-bandwidth processing* refers to instances where additional high-frequency energy (i.e., above approximately 4 to 5 kHz) is included in the speech signal through traditional processing (often carried out via low-pass filtering). *Frequency lowering* refers to conditions where the high-frequency portion of the speech signal is lowered, in some way, to a lower-frequency region. John understands that the speech signals used in the cited studies frequently underwent several forms of processing (e.g., low-pass filtering, frequency compression, frequency transposition, frequency translation) to accomplish the objective of the study. Keeping this in mind, the primary goal of his review was to examine, from a broad perspective, the effectiveness of these two signal-processing techniques for providing audibility of high-frequency speech energy.

Additionally, study participants were required to have sensorineural hearing loss and mean thresholds in the mild to moderately severe range in a sloping configuration. Specifically, hearing thresholds must fall within the normal/mild hearing loss range in the low-frequency region (i.e., below 1000 Hz) and slope to a moderate or moderately severe loss in the high-frequency region. Studies using participants with various degrees of hearing impairment were included only when John could separately analyze the results that were obtained from listeners with hearing thresholds comparable to his patient. This meant including studies where listeners had lesser or greater degrees of hearing loss than his patient, but John believed that only including studies where participants had precisely the same degree of hearing loss would not provide sufficient information from which to make an informed clinical decision.

Search Strategy

John searched for relevant studies using EBSCO, PubMed, Google Scholar, as well as journals from the American Speech-Language-Hearing Association (ASHA) and American Academy of Audiology (AAA). The following keywords were used in isolation and in combination:

- Mild-to-moderately severe
- High-frequency
- Hearing loss
- Amplification
- Frequency lowering
- Extended bandwidth

Information Retrieval

Seventy-three articles were retrieved based on review of the abstract and manuscript title. Of these, twenty-six were retained for additional review. Additional analyses yielded 18 articles that met the inclusion criteria of this review. Figure 1 provides a summary of the studies identified and those included or excluded at each step during the retrieval process. Specific details of each study are provided in Tables 1 and 2. The former contains studies conducted within the previous 10 years (i.e., 2006 through 2016), while the latter contains information from studies older than 10 years. John's discovered that many studies required listeners to identify speech in both quiet and noisy listening conditions. Therefore, to gain a thorough understanding of the data, his analysis focused on each listening condition individually.

Evaluating the Evidence

Summary of Results in Noise

A majority of the studies required listeners to identify the speech signal (e.g., phonemes, words, sentences) in listening conditions with competing background noise. Considering the cumulative results from all studies, extending the audible bandwidth to include more high-frequency information appears to enhance speech recognition for hearing-impaired listeners with hearing loss similar to John's patient, particularly in noisy listening conditions (e.g., Cox, Johnson, & Alexander, 2012; Pepler, Lewis, & Munro, 2106).

Results using frequency-lowering techniques by hearing-impaired listeners with comparable hearing sensitivity seem less promising. For example, Alexander, Kopun, and Stelmachowicz (2014) studied consonant identification in speech-shaped noise recorded through two clinically fit hearing aids (Widex® Inteo™ IN-9 BTE and Phonak Naída™ V). Results showed that while the nonlinear frequency compression (NFC) lowering technique improved recognition of phonemes from the fricative/affricate class, the frequency-transposition technique used in the study degraded consonant identification in noise. Additionally, Miller, Bates, and Brennan (2016) found that listeners with gradually sloping hearing losses did not show significant improvements in speech recognition from signals processed through three commercially available hearing aids equipped with frequency-lowering technology. In fact, significantly poorer sentence-recognition thresholds were found with activated frequency-lowering techniques (i.e., linear frequency transposition and frequency translation) as compared to inactive. With NFC active, sentence-recognition performance did not improve or decrease. The authors suggested that clinicians should take caution when activating frequency lowering for this population (i.e., listeners with gradually sloping hearing loss), as it may degrade speech recognition in noise for some listeners.

John also examined studies that provided high-frequency information through processing strategies that included additional high-frequency signal amplification. A recent study by Pepler, Lewis, and Munro (2016) examined consonant identification among 36 listeners with hearing impairment (18 with cochlear dead regions and 18 without dead regions). Listeners without cochlear dead regions showed significant improvements in consonant identification when including additional high-frequency speech energy. The authors reported that there is no evidence to support limiting high-frequency amplification for adults with at least a moderate hearing loss, particularly in noisy environments. Additionally, Levy, Freed, Nilsson, Moore, and Puria (2015) obtained sentence reception thresholds among normal-hearing and hearing-impaired listeners with a mild to moderately severe sensorineural hearing loss. Sentence reception thresholds significantly improved when extending the signal bandwidth from 4 kHz to 10 kHz when the speech and noise were separated in location. The authors suggested that increasing audibility of high-frequency spectral energy may improve speech-recognition performance in the presence of spatially separated noise.

Summary of Results in Quiet

Upon review of the retained articles, John found less evidence to support including additional high-frequency speech information in quiet listening conditions. For example, Amos and Humes (2007) found a small but significant improvement in final-consonant recognition for elderly hearing-impaired listeners when increasing audibility of this region. Horwitz, Ahlstrom, and Dubno (2008) found similar results when increasing the low-pass filter cutoff to include additional high-frequency spectral detail. Conversely, however, Turner and Cummings (1999) and Hogan and Turner (1998) found the use of high-frequency spectral information to have an adverse effect on speech recognition in quiet when audiometric thresholds exceeded 55 dB HL. The authors advised caution when providing gain above 4 kHz when thresholds fall within this hearing loss range and noted the need for verification measures to determine the utility of amplifying the high-frequency region.

Souza, Arehart, Kates, Croghan, and Gehani (2013) examined how frequency lowering using a form of frequency compression influenced speech intelligibility for adults with mild to moderate hearing loss. In quiet, no benefit in speech recognition was observed with the frequency-lowered speech when compared to unaltered speech. The authors suggested that listeners with the poorest high-frequency thresholds benefited the most from the frequency-lowering technique used in their study, but individuals with hearing loss similar to John's patient showed no benefit. All studies considered, John determined that there was limited evidence to support increasing access to high-frequency speech energy in quiet conditions for listeners with hearing loss similar to his patient.

Summary of Evidence

John also examined the quality of the evidence identified during his search. Using criteria described in Cox (2005), all of the studies were a minimum of level III (i.e., well-designed, nonrandomized quasi-experimental studies), which is considered to be a moderate level of evidence. Following a detailed review of all evidence obtained in his search, John determined that there is a need for randomized controlled experimental studies that directly compare speech recognition outcomes in quiet and in noise using each signal-processing technique. Many of the studies used simulated hearing aid processing or speech processed through computer programs and did not subject the speech signal to processing through clinically fit hearing aids. Although additional variables may complicate study design, studies using clinically available hearing aids that offer extended-bandwidth and frequency-lowering technologies can help inform clinical decision making regarding amplification of the high-frequency portion of the speech spectrum.

The Evidence-Based Decision

For Mr. Smith, it appears that John should begin with amplifying high-frequency speech energy through extended-bandwidth processing, keeping in mind the goal of improving speech-recognition performance in noisy listening environments. It is long established that many hearing aid users report poorer performance and dissatisfaction with their devices in degraded environments. In a recent MarkeTrak study, Abrams and Kihm (2015) reported that between 30 and 50% of respondents described substantial difficulty when attempting to recognize speech in noise. Given the data obtained in this Brief, the strongest evidence supports amplifying high-frequency speech energy through signal processing that includes as much unaltered high-frequency information as possible compared to techniques that artificially lower high-frequency spectral information. That said, audiologists should always verify hearing aid function through real-ear and aided speech-recognition measures and validate patient satisfaction in all listening environments. If John concludes that the current technique is unsuccessful at improving Mr. Smith's speech-recognition abilities, he should explore and offer additional signal-processing techniques to his patient. Souza et al. (2013) suggested that the use of high-frequency amplification techniques should be viewed in terms of the "audibility-by-distortion trade off" (p. 1354), which may vary substantially among listeners. As such, audiologists should consider each case individually and adjust the prescribed amplification technique accordingly.

When interpreting these results, John must acknowledge the lack of randomized controlled studies that directly examine speech-recognition performance between signal-processing techniques for amplifying the high-frequency portion of the speech spectrum. Clinicians would benefit from additional studies using currently available hearing aids that offer both signal-processing techniques (i.e., extended-bandwidth processing and frequency lowering). Such studies would inform clinical decision making for hearing healthcare providers when fitting amplification devices for listeners who require amplification of the high-frequency auditory region.

Authors' Notes

Jeremy J. Donai is an assistant professor at West Virginia University. He is the co-director of the Speech and Hearing Laboratory at WVU and teaches courses in anatomy and physiology, psychoacoustics, and amplification.

Jeremy C. Schwartz is a first-year AuD student at West Virginia University.

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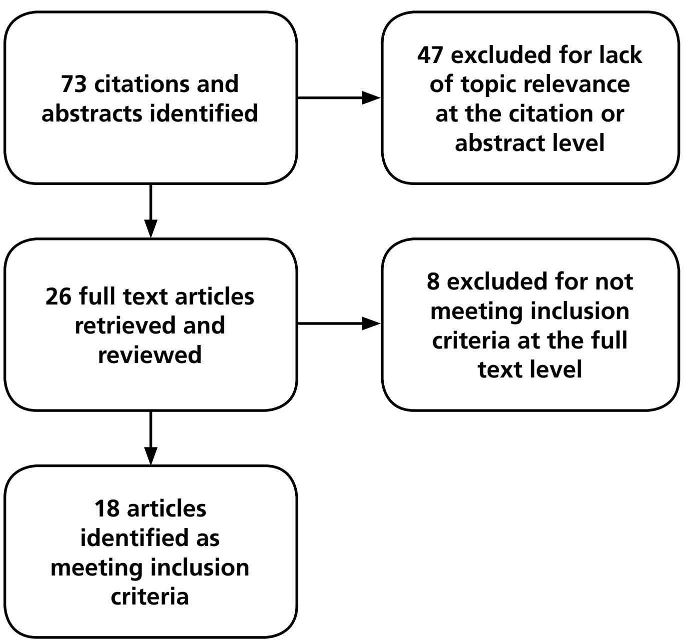

Figure 1. Flow chart for study inclusion/exclusion decisions

Table 1. Descriptions and Outcomes of Studies Published From 2006 to Present

Study	Design	Sample Description	Dependent Variable	Results	Implications
Alexander (2016)	Within-subject repeated measures design	14 participants with mild to moderate high-frequency sensorineural hearing loss (HFSNHL) 14 participants with moderately severe HFNSHL	Consonant and vowel recognition from nonsense syllables measured using various nonlinear frequency compression (NFC) parameters	Decreased vowel and consonant recognition at lowest start frequency (1.6 kHz). Significant improvements in detection of final /s/ and /z/ and for some VCV tokens with NFC.	No significant benefit on vowel recognition. Benefits of NFC limited to final /s/ and /z/ for variety of hearing losses. Low SF may degrade speech understanding, especially when combined with high compression ratio (CR).
Miller, Bates, & Brennan (2016)	Cross-sectional repeated measures design	10 adults with bilateral downward sloping HFSNHL	Signal-to-noise ratio required to achieve 50% correct performance (SNR-50) using the American English matrix sentence test in noise through three commercially used hearing aids	Mean SNR-50 thresholds for nonlinear frequency compression (NFC), linear frequency transposition (LFT), and frequency translation (FT) were -5.12, -5.55, and -.94 dB, respectively (with lower thresholds indicating better performance). Thresholds for WDRC processing technique were significantly better than thresholds for all frequency-lowering (FL) techniques.	Participants with gradually sloping hearing loss did not show significant improvements in speech recognition with FL techniques. Individuals with less severe HFSNHL may not benefit from FL. Caution when activating FL, as it may degrade speech recognition in noise for some listeners
Pepler, Lewis, & Munro (2016)	Mixed design	36 participants with mild to moderately severe SNHL 18 with cochlear dead regions and 18 without dead regions	Consonant identification using VCV nonsense syllables in quiet and in 20-talker babble processed through clinically fit hearing aids	Significant benefit when including HF speech signal information in noise for listeners without dead regions	No evidence to support limiting HF amplification in adults with a moderate hearing loss, especially in noise
Levy, Freed, Nilsson, Moore, & Puria (2015)	Mixed design	Experiment 1: 24 normal- hearing participants (thresholds ≤ 20 dB HL from 0.25 to 10kHz and speech discrimination scores of ≥ 92%). Experiment 2: 25 participants with mild to moderately severe SNHL and speech discrimination scores of ≥ 70%	Sentence reception threshold for Hearing in Speech Test sentences measured in two spatial configurations	Experiment 1: Sentence reception threshold improved significantly (3.0 dB) when signal bandwidth increased from 4 to 10kHz. Experiment 2: Sentence reception threshold improved significantly (1.3 dB) when extending signal bandwidth from 4 to 10 kHz and .5 dB when extending from 6 to 10kHz.	Extending the bandwidth from 4 to 10 kHz can improve the ability of normal and hearing-impaired listeners to understand speech in the presence of spatially separated noise.

Table 1. Descriptions and Outcomes of Studies Published From 2006 to Present (continued)

Study	Design	Sample Description	Dependent Variable	Results	Implications
Alexander, Kopun, & Stelmachowicz (2014)	Mixed design	24 normal-hearing listeners 24 hearing-impaired listeners (normal hearing or mild loss ≤ 40 dB HL for frequencies ≤ 1 kHz, and moderate to moderately severe SNHL [45 to 70 dB HL] for frequencies ≥ 3 kHz)	Identification of VCs (fricative and affricate consonants) in speech-shaped noise recorded through two different hearing aid types (Widex Inteo IN-9 BTE and Phonak Naida V UP BTE) in various spectral conditions	Hearing-impaired listeners performed significantly worse with frequency transposition (FT) than any of the other conditions. Performance increased substantially in the wide band (WB) and spectral envelope decimation (SED) conditions. Performance increased with NFC on versus NFC off.	NFC can provide benefit for fricative/affricate identification for listeners with mild to moderate SNHL without introducing additional phonemic confusions. FT is not recommended for individuals with mild to moderate HFSNHL because it may negatively impact identification.
Souza, Arehart, Kates, Croghan, & Gehani (2013)	Mixed design	26 listeners with moderate high-frequency loss 14 individuals not considered hearing-aid candidates	Low context sentence recognition (Connected Speech Test) as a measure of intelligibility and two sentences as a measure of sound quality in quiet and noise	Group data showed no benefit, in terms of sentence intelligibility, of frequency lowering for individuals with mild to moderate HFSNHL. Individual data indicated that participants with poorer HF thresholds showed improved sentence recognition with frequency lowering.	No convincing evidence indicating that consistent use of frequency compression will increase intelligibility for adults with hearing impairment FC should not be universally prescribed for all patients with mild to moderate sensorineural hearing loss. Greatest benefit of FC for listeners with poorest thresholds
Cox, Johnson, & Alexander (2012)	Double-blinded, nonrandomized intervention	18 matched pairs, one with dead regions and one without dead regions	Aided speech recognition using the Computer Assisted Speech Perception Assessment (CASPA) in quiet and BKB-SIN test in noise under various signal bandwidth conditions	Both groups benefited from high-frequency cues, with those without dead regions showing more benefit in a quiet laboratory setting. In noise, listeners without dead regions benefited from high-frequency cues, while those with dead regions did not show benefit but did not show reduced performance with additional high-frequency cues.	Supports the use of a generic gain prescription similar to National Acoustic Laboratories (NAL) method for maximizing speech recognition The authors advised against limiting high-frequency gain prescription solely because of dead regions in one or two frequency regions.

Table 1. Descriptions and Outcomes of Studies Published From 2006 to Present (continued)

Study	Design	Sample Description	Dependent Variable	Results	Implications
Füllgrabe, Baer, Stone, & Moore (2010)	Mixed design	15 hearing-impaired listeners (mild to moderate SNHL) and 4 normal-hearing listeners	Identification and/or detection of running speech, isolated words, or VCV nonsense syllables processed using CAMEQ2-HF algorithm	CAMEQ2-HF improved audibility in the high frequencies (above 5kHz). Hearing-impaired listeners performed better on detecting final /s/ and /z/ in wider bandwidth condition (7.5 vs. 5 kHz). Identification of VCV nonsense syllables significantly improved with increasing bandwidth (from 5 to 7.5 kHz) for NH listeners but not for hearing-impaired listeners.	Gains prescribed by CAMEQ2-HF were sufficient to restore audibility for hearing-impaired listeners for male and female talkers, even for 7.5 to 10 kHz frequency band. The authors suggest that the lack of improvements in consonant identification associated with increases in signal bandwidth among hearing-impaired listeners is less encouraging.
Moore, Füllgrabe, & Stone (2010)	Mixed design	8 normal-hearing (NH) subjects (audiometric thresholds ≤ 15 dB HL for octave frequencies between 0.125 and 8 kHz as well as 9 and 10 kHz) 16 subjects with symmetrical hearing loss and a PTA HL at 2, 3, and 4 kHz < 60 dB HL	Speech recognition from audio-visual adaptive sentence lists (ASLs) measured in quiet and noise, with various reverberation times and hearing aid processing parameters	Small but significant benefit of increasing the cutoff frequency from 5 to 7.5 kHz for both groups for the spatially separated, but not collocated, condition Benefit of aided listening was higher in the spatially separated condition than the co-located condition, but improvements were noted in both.	Benefit observed when increasing the upper cutoff frequency (from 5 to 7.5 kHz, for example) in a simulated hearing aid would be greater under conditions where the target and background were spatially separated than where they were co-located. HI subjects benefit more from aided listening in spatially separated conditions than in a co-located condition. Substantial differences may exist in benefit from extended-bandwidth processing among listeners.

Table 1. Descriptions and Outcomes of Studies Published From 2006 to Present (continued)

Study	Design	Sample Description	Dependent Variable	Results	Implications
Horwitz, Ahlstrom, & Dubno (2008)	Mixed design	18 younger adults with normal hearing (thresholds ≤ 20 dB HL at octave frequencies from 0.25 to 8 kHz 16 older adults with sloping high-frequency sensorineural hearing loss (pure tone thresholds above 2 kHz ranging from 55 to 80 dB HL)	Speech recognition measured for nonsense syllables low-pass filtered in one-third-octave steps between 2.2 and 5.6 kHz in quiet and noise processed with gain-frequency response individually prescribed (NAL-R)	Experiment 1: Small but significant benefit in consonant recognition for hearing-impaired listeners using nonindividualized gain-frequency response through 4.5 kHz Experiment 2: Significant benefit in consonant recognition for hearing-impaired listeners using nonindividualized and individualized gain-frequency response with each additional high-frequency speech band up to and including 5.6 kHz Experiment 3: Significant benefit in consonant recognition in quiet and in speech-shaped noise for hearing-impaired listeners using individualized gain-frequency response with each additional high-frequency speech band up to and including 5.6 kHz	Findings of the current study support the clinical practice of providing some degree of high-frequency amplification for listeners with high-frequency hearing loss between 55 and 80 dB HL. No evidence of a degree of hearing loss above which high-frequency amplification was detrimental High-frequency amplification may benefit hearing-impaired listeners more so in noise than in quiet conditions.
Amos & Humes (2007)	Mixed design	36 elderly hearing-impaired (EHI) and 24 young normal-hearing (YNH) listeners	Word recognition using Boothroyd's AB word-recognition test in multiple-bandwidth conditions and signal-to-noise ratios	Small, but significant, increase in final consonant recognition in quiet for EHI listeners No significant improvement in speech recognition with the addition of spectral energy from 3.2 kHz to 6.4 kHz. No degradation in performance was found.	No immediate benefit to speech recognition with increases in speech signal bandwidth from 3.2 kHz to 6.4 kHz suggests providing gain to the high-frequency region may not be beneficial or detrimental.

Table 1. Descriptions and Outcomes of Studies Published From 2006 to Present (continued)

Study	Design	Sample Description	Dependent Variable	Results	Implications
Plyler & Fleck (2006)	Mixed design	20 hearing-impaired listeners, 11 with mild to moderate SNHL and 9 with mild to moderately severe SNHL	Sentence recognition measured using the Connected Speech Test (CST) and the Hearing in Noise Test (HINT) in quiet and noise following two 6-week trial periods	High-frequency amplification did not significantly improve speech recognition in quiet for either group. Significant main effect for amplification type (minimum vs. maximum HF), suggesting significantly improved speech recognition in noise for both groups	High-frequency amplification should initially be provided to high-frequency regions in the presence of mild to severe hearing loss, particularly in noisy environments.

Table 2. Descriptions and Outcomes of Studies Published Prior to 2006

Study	Design	Sample Description	Dependent Variable	Results	Implications
Baer, Moore, & Kluk (2002)	Mixed design	10 subjects with HFSNHL 5 with high-frequency cochlear dead regions 5 without dead regions	Identification of VCV nonsense syllable consonants in noise in various bandwidths utilizing simulated hearing aid processing	Significant main effect of filter cutoff frequency was identified for listeners without dead region. Improvements in identification were found with increasing cutoff frequency from 2 kHz (55.2%) to 7.5 kHz (79.1%).	For patients without high- frequency dead regions, amplification of the high frequencies can be beneficial for recognizing speech in noise.
Vickers, Moore, & Baer (2001)	Mixed design	10 subjects with HFSNHL 7 with high-frequency cochlear dead regions 3 without dead regions	Identification of VCV nonsense syllable consonants in quiet in various bandwidths utilizing simulated hearing aid processing	Significant main effect of filter cutoff frequency was identified for 3 listeners without dead regions. Improvements in identification were found with increasing cutoff frequency from 2 kHz (65.1%) to 7.5 kHz (77.2%).	For patients without high-frequency dead regions, amplification of the high frequencies can be beneficial. When a dead region is not present, amplification should be provided over as wide a bandwidth as possible.
Turner & Cummings (1999)	Mixed design	5 listeners with normal hearing (thresholds of better than or equal to 20 dB HL at all audiometric frequencies) 11 listeners with various degrees of SNHL (10 with sloping SNHL)	Consonant identification using nonsense (VC) syllables at various presentation levels	Decreased consonant recognition when the high-frequency audiometric threshold exceeded 55 dB HL. When hearing loss exceeded 55 dB HL in the high-frequency regions, the efficacy of providing audible speech information decreased.	Caution should be given to providing high-frequency amplification for listeners with audiometric thresholds exceeding 55 dB HL. A clinician may want to test whether adding additional amplification to frequency regions above 3 kHz produces a measurable improvement in speech recognition for patients exhibiting more than a mild to moderate high-frequency loss.

Table 2. Descriptions and Outcomes of Studies Published Prior to 2006 (continued)

Study	Design	Sample Description	Dependent Variable	Results	Implications
Hogan & Turner (1998)	Mixed design	5 subjects with normal hearing sensitivity (thresholds better than 20 dB HL from 250 to 8,000 Hz) 9 subjects with relatively normal hearing thresholds or minimally impaired sensitivity (35 dB HL or better) at 250 and 500 Hz and varying degrees of hearing loss for higher frequencies	Identification of nonsense syllables low-pass filtered at a number of cutoff frequencies	Listeners with mild losses benefited from additional high-frequency speech information. As hearing loss increased, benefit associated with extending the bandwidth decreased. As thresholds increased beyond 55 dB HL, efficiency (defined as how well the hearing-impaired listeners used speech information presented at audible levels and at various frequencies compared to normal hearing listeners) decreased.	Clinicians should use caution when providing amplification above 4.0 kHz when hearing loss in those regions is greater than 55 dB HL. Providing amplification to higher-frequency regions may, however, benefit individuals with mild to moderate losses (less than 55 dB HL).
Skinner (1980)	Repeated-measures design	6 adult male listeners with thresholds in the test ear less than 20 dB HL from .125 to 1 kHz and greater than 40 dB HL from 2 to 4 kHz	Word identification on the Pascoe High-Frequency Word List with five amplification systems; one with a uniform frequency response and 4 with increasing amounts of high-frequency emphasis	Significant improvement in word identification scores with increasing intensity and increasing high-frequency emphasis	Maximizing audibility such that the speech signal falls within the listener's dynamic range is recommended in hearing aid fittings.
Schwartz, Surr, Montgomery, Prosek, & Walden (1979)	Repeated-measures design	10 male subjects with bilaterally symmetrical high-frequency cochlear hearing loss	Word and consonant discrimination in quiet and in the presence of noise in 3 conditions: (1) unaided, (2) wearing his own aid, and (3) while wearing the experimental high-pass instrument	No significant difference (0–4% across conditions) in word and consonant recognition in quiet for the three conditions Significantly better performance (approximately 8–10% across conditions) with the experimental high-pass aid compared to the patient's own aids in the presence of competing speech babble.	Data suggest that the high-pass instrument seemed to minimize the adverse effects of competing noise on speech discrimination. Increasing access to high- frequency information may help to reduce consonant confusion in noise.