Frequency Lowering in Hearing Aids
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Overview: Frequency Lowering
- What is it?
- Why use it?
- Techniques in hearing aids
- Research findings
- Verification

What is Frequency Lowering?
- A method of increasing access to a wider range of spectral content
- Picks up where traditional amplification leaves off
  - Amplification 'moves' the level of soft sounds into a range that is audible for the patient
  - Frequency lowering moves the spectral content of high-frequency sounds to a region that is audible for the patient

Concept Behind Frequency Lowering

Frequency Lowering in Hearing Aids
- Not a new concept for severe hearing loss
  - Experimental
    - Vocoding and slow playback techniques (1960-1970’s)
    - Wearable device
      - Oticon TP 72 (Johannson, 1961)
  - Oldest technique currently in use: since 1991

Research Interest

- Why the renewed interest?
  - New technologies allow for new techniques
  - New research findings
  - New target population: mild-moderate hearing loss

Source: Lejon (2009)
Industry Interest

- # of Hearing Aid Models with Frequency Lowering
- Widex
- June 2008: First products for mild to moderate losses

Controversy

- While the speech code is relatively 'scale invariant,' it is heavily dependent on frequency
- No currently implemented DSP strategy has as much potential to change the identity of individual speech sounds
- Potential to make speech understanding worse because low-frequency information has to be altered to accommodate displaced high-frequency information

Why Even Consider It?

- Rationale varies depending on severity of loss
  - Moderately severe or greater loss
  - Precipitous high-frequency loss
  - Mild to moderate loss
- Influenced by the information we hope to 'recover' from the speech spectrum
  - Different goals for different hearing losses

Potential Benefits of Frequency Lowering

**What do we hope to achieve?**

**Answer:** some of the same benefits as increasing audible bandwidth with traditional amplification - if we could

Moderate to Severe Loss

- Average Speech
- Inaudible

**Reason:** make some of this information available to the user
Moderately Severe Losses (or worse)
- Limitations in hearing aid gain and feedback
  - Important mid-frequency information is inaudible
- High-frequency dead regions
  - May not make as effective use of amplified high-frequency information and may even perform worse when made audible
  - E.g., Moore, 2004; Baer et al., 2002; Vickers et al., 2001
- Rationale
  - Provide users with information that is normally available to those with less severe hearing loss (~5kHz)
  - Avoid dead regions

High-Frequency Dead regions
- A form of uncontrolled frequency lowering (transposition)
  - Signal detected at an off-frequency place on the basilar membrane
  - Detection occurs at same place where information is processed more normally
  - Unknown re-coding process: tonal stimuli may sound noise-like/distorted

Precipitous Losses
- Need help that conventional amplification cannot provide
  - Marginal candidates for amplification
  - Limited frequency range with which to amplify speech because of difficulty getting sufficient gain in regions of hearing loss
    - Too normal to amplify and too severe to amplify
- Rationale
  - Help users make better use of a very limited residual bandwidth of audibility (e.g., < 2000 Hz)

Mild to Moderate Losses
- A novel application of frequency lowering
  - Extend bandwidth of information to ‘ultra’ high frequencies beyond that normally achievable with conventional amplification (>5 kHz)
  - Audible bandwidth limited by hearing aid, not by hearing loss per se:
    - Receiver output
    - Maximum gain without feedback
    - Manufacturer decisions to limit DSP (sampling rate, processing delay, current drain, etc.)

Hearing Aid Limitations
- Moore et al. (2008): To partially restore audibility for 65 dB hearing loss at 10 kHz requires an effective insertion gain of 36 dB (90 dB SPL)
  - Could only be achieved in 25 of 62 ears
    - 68 dB HL average at 10 kHz
  - Possible unpleasant, harsh, or tinny sound quality, or loudness discomfort
- Wireless streaming limitations
  - Audio bandwidth of Bluetooth is 7.5 kHz
Typical HA Receiver Response

Gain is least where hearing loss is greatest

Before Filtering

Filtered by Receiver Response

Rationale: make frication audible

What’s Being Missed?

Importance of High Frequencies

A decrease in redundancy and context increases the relative importance of high-frequency information
Results are for filtered speech in quiet; effects of noise?

Even NH adults listening in quiet benefit from high frequency information
Relative importance increases in challenging listening conditions and with decreased linguistic context

Fricatives and affricates account for about 50% of English consonants

/ʃ/, /ʒ/: about 8% of spoken English consonants (Rudmin, 1983)
Significant implications for morphological development

Over 20 linguistic uses for /ʃ/, /ʒ/: plurality, third person present tense, past vs. present tense, to show possession, possessive pronouns, contractions (Rudmin, 1983)
**Developmental Importance**

- **Fricative Production**: Despite early intervention, toddlers with mild to moderate hearing loss produce very few fricatives or affricates (Moeller et al., 2007)
  - While they start to catch up with their normal-hearing peers on production of other sound classes, they fall further behind in production of fricatives and affricates

- **Morpho-Syntactic Development**: 5 to 7 year-olds identified late (2-3 years) less consistently and less accurately use the morpheme /s/ (Moeller et al., 2010)
  - Production accuracy of /s/, /z/ in children with hearing aids is 15-18% worse than children with CI's (Grant et al., 2002)

**Conclusion:**
Conventional hearing aids do not provide the high-frequency cues necessary for normal development of speech even cases of mild to moderate loss

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**Benefit of Extending Bandwidth**

- **Increasing BW >5 kHz in the laboratory (no lowering)**
  - Improved speech recognition
    - Especially fricatives (Stelmachowicz & colleagues)
    - Sentences in quiet/noise (Hornsby & Ricketts, 2006/Hornsby, 2007)
  - May depend on audiometric configuration (Hornsby et al., 2011)
  - Improved novel word learning by children (Pittman 2008)

- **Improved speech clarity and music quality**
  - Moore & Tan (2003):
    - For normals, upper cutoff for speech = 10.8 kHz and for music = 16.5 kHz
  - Ricketts et al. (2008):
    - Impaired listeners preferred 9-kHz bandwidth when slope of loss was <7.5 dB/oct.
  - Sjolander & Holmberg (2009):
    - Listeners using a hearing aid with extended high-frequency gain generally preferred a 10-kHz bandwidth over 8-kHz bandwidth for listening to music
  - Füllgrabe et al. (2010); Moore et al. (2011)
**Benefit of Extending Bandwidth**

**Increasing BW >5 kHz in the laboratory (no lowering)**
- **Less effortful listening** (Karlsen et al., 2006)
- **Improved localization** (Best et al., 2005; Brungart & Simpson, 2009)
  - Pinna cues: elevation, front/back
- **Improved spatial unmasking** (Hamacher et al., 2005; Moore et al., 2010)
  - Head shadow increases with frequency

**Benefit of Extending Bandwidth**

It remains to be seen whether these same benefits be achieved using frequency lowering

**Mild to Moderate Losses**

**Rationale for frequency lowering**
- Provide users with information that is beyond the bandwidth normally achievable with conventional amplification (>5 kHz)
- Improve perception (and production) of fricatives, especially /s/
- Possibly reduce listening fatigue and improve sound quality by providing a fuller, richer signal

**Summary of What and Why**

**Why use frequency lowering?**
- Hearing loss and other reductions in redundant speech information and context (e.g., noise and maturation) increase the importance and need for high-frequency information
- **Precipitous losses**
- Make better use of a very restricted bandwidth of audibility
- **Moderately severe or greater losses**
- Extend the bandwidth of information to that which is normally achievable with conventional amplification (>5 kHz)
- Avoid excessively amplifying dead regions
- **Mild to moderate losses**
- Extend the bandwidth of information beyond the bandwidth normally achievable with conventional amplification (<5 kHz)
- Improve perception (production) of fricatives, especially /s/, which are a significant problem, despite early intervention

**Techniques for Frequency Lowering in Hearing Aids**

**Terminology**

- **Source Region**
  - The frequency range that is subject to lowering
  - Start frequency: lowest frequency in the source region
- **Target Region**
  - The frequency range where lowered information is moved to
  - Frequency Compression (squeeze)
    - Target region is contained within the source region
    - Bandwidth of the source region is reduced
    - Start frequency (even 0 Hz) is like an anchor that does not move
  - Frequency Transposition/Spectral Feature Translation
    - Less overlap between target and source regions
    - Bandwidth of the source region is not reduced
    - Start frequency is moved to a lower frequency
Techniques in Today’s Hearing Aids

- **Dynamic Linear Frequency Compression (DLFC)**
  - Widex: “Audibility Extender” (AE) - Introduced in 2006
  - Nonlinear Frequency Compression (NFC)
  - Starkey: “Spectral iQ” - Introduced in 2011

A Classification Scheme

- **Activation**
  - Input Dependent
  - Always Active
  - AVR (linear @ 0 Hz)
  - Phonak (nonlinear @ start)
  - Starkey (feature lowering)
  - Widex (peak lowering)

Dynamic Linear Freq. Compression

- **Proportional** on a linear scale
  - ‘Frequency divider’: e.g., DFC = 5.0 means that 5 kHz will move to 1 kHz (or, 8 kHz to 1.6 kHz) → pitch is changed
  - Spectral peak relationships are maintained within a compressed segment
  - Over-sampled input leads to “slow-play” effect
  - Sampling rate output < input by (L/DFC)
  - From 0 Hz to upper limits of mic & DSP

Dynamic Linear Freq. Compression

- **Dynamic switching behavior**
  - All or none: only when needed the most
  - Spectral balance detector
  - All when energy >2.5 kHz is greater than <2.5 kHz, otherwise none
  - Most likely noisy fricatives and bursts associated with stop and affricate consonants
  - Dominant low frequency energy (especially vowels) is unaltered → more natural sound quality
  - Pitch for voiced speech is mostly unaltered

- “Dynamic consonant boost” to increase lowered-signal by up to 16 dB
- **Candidacy**: Moderately-severe to profound, overlaps with CI candidacy

Dynamic Linear Freq. Compression

- **Input-Output Functions**

- **Output**
  - Level
  - DFC

- **Input**
  - Level
  - Freq.
With precipitous losses, detection of tonal sounds might be very poor or absent for frequencies < 2500 Hz where the hearing drops out because frequency-lowering switch is not triggered. Detection of tonal sounds > 2500 Hz significantly improves again because switch is activated.

Start frequency is start of inaudibility (e.g., dead region)

Source region starts about ½ octave below start freq.

Spectral peak detector: strongest peak in source region

Octave-wide band (re: target destination) is filtered around source peak and copied (original peak is maintained) down one octave.
### Linear Frequency Transposition

- **Source**
- **Target**

- 6 kHz 'start'
- 1k
- 1k
- 4 kHz Limit
- 5k
- 6k
- *Behavior is dynamic: exact frequency location of transposed signal (source & target) varies depending on the short-term input spectrum*
- *Always active: may minimize signal discontinuities and artifact*
- *Harmonic relationship b/w original & transposed signals maintained*  
  - May be more natural and pleasant
  - Pitch is unaltered

- **Concerns:**
  - Masking between the dual sources of information
  - How does the perceptual system differentiate between a transposed high-frequency peak and an un-transposed low-frequency peak?

### AE Frequency Reallocation Table

<table>
<thead>
<tr>
<th></th>
<th>Basic AE</th>
<th>Expanded AE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Freq.</td>
<td>Source Region</td>
<td>Target Region</td>
</tr>
<tr>
<td>630</td>
<td>645-1260</td>
<td>223-630</td>
</tr>
<tr>
<td>800</td>
<td>566-1600</td>
<td>283-800</td>
</tr>
<tr>
<td>1000</td>
<td>707-2100</td>
<td>354-1000</td>
</tr>
<tr>
<td>1250</td>
<td>884-2500</td>
<td>442-1250</td>
</tr>
<tr>
<td>1600</td>
<td>1315-3320</td>
<td>566-1600</td>
</tr>
<tr>
<td>2500</td>
<td>1768-5000</td>
<td>884-2500</td>
</tr>
<tr>
<td>3200</td>
<td>2263-6400</td>
<td>1131-3200</td>
</tr>
<tr>
<td>4000</td>
<td>2828-7000</td>
<td>1414-3500</td>
</tr>
<tr>
<td>6000</td>
<td>4242-7000</td>
<td>2121-3500</td>
</tr>
</tbody>
</table>

*Approximate Values: Transposed signals extend beyond these regions with decreasing amounts of gain*

### ‘Audibility Extender’ (AE)

- **Basic AE:** dominant peak shifted down by 1/2 (octave), source region begins 1/3 octave below start frequency
- **Expanded AE:** dominant peak shifted down by 1/3, source region begins 1/3 octave above frequency start, peak shift from basic AE remains

### AE Frequency Transposition

- **Input:**
- **Output:**

  - Actual start
  - Start frequency
  - Down by 1/2
  - Down by 1/3
  - (octave), source region begins ½

### Candidacy

- **Kuk et al. (2009):** only those with:
  - Dead regions
  - Profound loss in the high frequencies with moderate loss in the mid and low frequencies
  - Precipitous loss in high frequencies
  - Loss should not be too severe in low frequencies, otherwise cochlear distortion, along with high gain and low MPO could further distort the transposed signal

- **Behavior is dynamic:** source content mix with content in target region

- **Always active:** may minimize signal discontinuities and artifact

- **Harmonic relationship** b/w original & transposed signals maintained
  - May be more natural and pleasant
  - Pitch is unaltered
Linear Frequency Transposition

- Only a portion of the spectrum around the peak is transposed
  - Limits the amount of masking and eliminates need for frequency compression
  - High-frequency energy is often diffuse with a broad peak → potentially useful information about gross spectral shape is discarded
- Transposed and un-transposed signals are mixed
  - Already mentioned issue with masking and segregation
  - Might transpose unwanted high-frequency background noise and decrease SNR

Nonlinear Frequency Compression

- Adjustable start frequency and compression ratio
- The higher the number, the more the input compression band (CB) is condensed; very closely corresponds to the bandwidth reduction on an ERB_N scale:
  \[ CR = \frac{\text{input CB}(\text{ERB}_N)}{\text{output CB}(\text{ERB}_N)} \]
  - Actual numbers below:
  - 6 ERB_N (in)
  - 3 ERB_N (out)

How Nonlinear Freq. Comp. Works

Processing Limits: What You See

- Lowest nominal start freq. = 1500 Hz
- Highest nominal start freq. = 6000 Hz
  - 4000 Hz in power device (Naída UP)
- Compression ratio = 1.5 – 4.0
  - Nonlinear on Hz scale (close to linear on ERB_N scale)

Processing Limits: What You Don’t See

- Phonak CORE (pre-2011)
  - Input compression band is always < 4500 Hz
  - Max. input frequency is always ≤ start + 4500 Hz, but no greater than ≈10,000 Hz
    - (6000 Hz in power device, Naída UP)
- Phonak Spice (2011)
  - Max. input frequency = 10,000 Hz
    - (maybe limited by receiver output)
  - No additional limitation in frequency compression bandwidth
NFC for Moderately Severe Loss

Flattened formant transitions

NFC for Mild-Moderate Loss

Flattened formant transitions

Spectral Feature Translation

- **Spectral Feature**: algorithm uses a classifier that looks for spectral features in the high-frequency spectrum that are characteristic of speech
  - Linear predictive coding: uses a source-filter model of the speech production system to characterize the signal
- **Translation**: features are synthesized at a lower frequency
  - Modifies the filter by adding the high-frequency peak in a lower frequency region
  - Uses the same source (i.e., harmonics are unaltered)

(Salus, personal communication)
Like AVR and unlike Widex and Phonak, frequency lowering is dependent on the input.

Because lowering is triggered by a high-frequency speech feature (i.e., frication), concerns about transposition that is always active are minimized:
- Masking and perceptual segregation of mixed signals
- Lowering of unwanted high-frequency background noise which can decrease SNR

Like Widex in that a portion of the high frequency information centered around the peak in the target band is lowered:
- Does it in a way that maintains the harmonics of the source band
- Mixes the lowered and un-lowered spectra

Unlike Widex and Phonak, does not roll off the high-frequencies beyond the 2 upper channels (> 5.7 kHz), which minimizes the risk that the clinician might unintentionally limit audible bandwidth

(Spectral Feature Translation)

**Two Controls**

1) **Bandwidth of the source band**
- 7 settings based on the high-frequency thresholds
- 2 defaults: a) severe-to-profound loss, b) moderate hearing loss
- Presumably, this affects the target band location
- Lower limit that peak information is lowered is somewhere between 1000-1200Hz
- The mapping of source to target band has not been revealed

2) **Gain of the lowered signal (0-10 dB)**
- i.e., the mixing ratio of lowered and un-lowered signals

(Spectral Feature Translation)

**Candidacy**

Recommended that all of the following be met:

1) Slope ≥ 25 dB per octave
2) Thresholds from 250-1000 Hz: ≤ 55 dB HL
3) Thresholds from 4000-8000 Hz: ≥ 55 dB HL
4) At least 1 threshold from 1000-3000: ≥ 55 dB HL

(Spectral Feature Translation)

**Summary of Techniques**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Activation</th>
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<tbody>
<tr>
<td>Compression</td>
<td>Always Active</td>
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<td>Transposition</td>
<td>Input Dependent</td>
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<td>AVR (linear @ 0 kHz)</td>
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<td>Widex (peak lowering)</td>
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</tbody>
</table>

Research Findings
Effectiveness - A Few Points to Consider

Re-coded information must go somewhere
- Regions that would be otherwise amplified normally
- Concern is not so much fidelity of re-coded information as it is newly introduced distortion and sound quality in the regions it is moved to
- A successful fitting requires giving the patient more than is taken away

Worse!

Amount of Speech Re-coding (Distortion of Audible Bandwidth)

DO NOT HARM
Depends on interaction b/w hearing loss & re-coding technique

Effectiveness - More Points to Consider

Perhaps the focus should be individuals in addition to group means
- Interactions with audiometric configuration, peripheral integrity, cognitive status, etc. are expected

Benefit may not always manifest as improvement in speech intelligibility, but perhaps, ease of listening and effort (like noise reduction), production accuracy, etc.

Period of re-learning or acclimatization?

Effectiveness - A Few Points to Consider

While re-coded information may not precise, the goal is to provide enough of it for top-down processes to reduce uncertainty and use other acoustic cues and context to fill in missing content

Process of perceiving individual speech sounds may be a matter of knowing more about what they are not than what they are (Jakobsen & Halle, 1956)

Dynamic Linear Freq. Compression

‘Meta-analysis’ by Simpson (2009)
- Compared to conventional devices: about half of the children (13/28) and one third of the adults (6/18) demonstrated significant increases in speech understanding with the DLFC, ranging from 10-20%

Lack of homogeneity within and between studies
- Devices varied from analog body worn to digital BTEs
- High attrition rates due to consideration of CI or cosmetic reasons
- High repair rates were noted
- Listeners with more severe loss seemed to benefit most
- Those who were fit earlier and those who were in oral communication programs seemed to benefit more
- Possible confound with extra low-frequency gain
**Frequency Transposition – Adults**
- Kuk et al. (2009)
  - 8 adults with severe-to-profound loss > 2kHz
  - Micro BTEs, 20-30 minutes daily training for 1 month, tested over 2 month period
  - After 2 months, fricative perception improvements of 5-10% increased to about 20%
  - Some decrement initially (confusion) for other consonants (esp. stops and nasals)
  - After 2 months either no difference (stops, nasals) or some improvement < 10% (affricates, glides, & liquids)
  - No degradation/improvement of performance in noise
- Kuk et al. (2011): no training effect for control

**Frequency Transposition – Children**
- Auriemo et al. (2009)
  - 10 children (6-13 yrs.) with severe-to-profound loss > 3kHz
  - 6 weeks of training with transposition and 3 weeks without
  - 5-10% improvement in consonant identification (esp. voiceless) at 50 dB HL presentation level in quiet
  - Poorest performers with FT de-activated had greatest improvement when it was activated
  - Production accuracy of /s/ and /z/ improved by 10%

**Nonlinear Freq. Comp. – Adults**
- Simpson et al. (2005)
  - Experimental body worn device for 4-5 weeks
  - 17 experienced hearing aid users with moderate to profound loss
  - Start frequency ranged from 1.6-2.5 kHz
  - Monosyllabic words: about half (8) had significant improvement compared to conventional aids, 8 showed no difference, 1 was worse
  - For the former, place of articulation and frication improved over 10%

**Nonlinear Freq. Comp. – Adults**
- Simpson et al. (2006)
  - 7 listeners with precipitous loss, start frequency = 1.0-1.6 kHz
  - Alexander: alteration of pitch and sound quality are associated with these start frequencies
  - No significant improvement, except one in noise, some new confusions
  - Compression parameters not individually chosen, 3 non-experienced users only wore device about 2 hours/week

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**Nonlinear Freq. Comp. – Adults**
- Glista et al. (2009)
  - Prototype BTE for 4 weeks (NFC activated/deactivated)
  - 8 of 13 users with severe-to-profound loss showed significant improvement, especially for plural recognition, with no significant effect on vowel perception
  - Start frequency ranged from 1.5 to 4.0 kHz
Nonlinear Freq. Comp. – Adults

- Bohnert et al. (2010)
  - Commercial device compared to subjects own devices
  - 7 of 11 listeners with severe to profound loss showed some improvement for sentences in noise, 4 performed more poorly
  - Acclimatization for subjective ratings (i.e., perceived benefit, own voice, etc. continued to improve after 4 months of use)

Nonlinear Freq. Comp. – Children

- Wolfe et al. (2011)
  - 15 children (5-13 yrs.) with moderate to moderately-severe loss
  - 6 months with commercial product aimed for children
  - Significant improvement after 6 weeks on plurals and consonant identification, which further improved after 6 months
  - Improvement in noise (SRT) only after 6 months
  - No control or withdrawal condition → cannot rule out maturation

Summary of Research Findings

- Dynamic Linear Frequency Compression
  - Severe-to-profound loss starting < 2.5 kHz
  - Normal to severe low-frequency hearing
  - Documented benefit for 1/2 of the children and 1/3 of the adults
- Frequency Transposition
  - Profound loss in the high freq. and moderate loss or better in low freq.
  - Should not be used to extend high-freq. BW for mild to moderate loss
  - Improvement in fricative perception in adults and children
  - Strong acclimatization effect lasting at least 2 months
- Nonlinear Frequency Compression
  - Improvement for fricatives/affricates in adults and children with mild-to-moderate loss and moderate-to-profound loss
  - Exception for precipitous loss > 1.5 kHz where low start frequency create more harm than benefit
  - Mild acclimatization for speech perception

Alexander et al. (2008)

- Efficacy of frequency lowering > 4 kHz
  - 24 adults with normal hearing
  - 24 adults with mild to moderate loss
    - Only 11 were regular hearing aid users

- Are error patterns a function of the frequency lowering, the hearing loss, or both?

Overall Percent Correct

<table>
<thead>
<tr>
<th># of HI Listeners with improvement (n=24)</th>
<th>Overall Percent Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nu FT</td>
<td>Nu FT (no)</td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>
Conclusions: Alexander et al. (2008)

Frequency transposition
- Substantially increased confusions, esp. [H/,/th-/] and [/v/, /THv/]
- For NH, place errors for /s/ and /z/ were new
- Errors are due to FT, not hearing loss

Nonlinear frequency compression
- NFC (6k) shows little harm/benefit compared to No NFC for HI
- 75% of HI listeners benefited from NFC (6k) and/or NFC (10k)

Follow Up Study

12 HI listeners returned
3 conditions
- No FC
- FC (10k) in device
  - 4.6 kHz start, 2.8:1 CR
- Wideband
Significant improvement for FC (10k) in device compared to No FC
- p < 0.01 (Wilcoxon)
- Worst performers with No NFC showed most benefit

Alexander (2010)

Consonants (n = 12)
- 120 nonsense syllables (vCv) presented in speech-shaped noise at 10 dB SNR
  - 20 consonants
  - 3 vowel contexts (i/ai/, /I/, /u/)
  - 2 talkers (adult male and female)

Vowels (n = 10)
- 72 nonsense syllables (h-V-d) presented in speech-shaped noise at 6 dB SNR (Hillenbrand et al., 1995)
  - 12 vowels
  - 6 talkers (2 adult males, 2 adult females, 1 boy, 1 girl)

Alexander (2010) Summary

For all talkers and all speech classes, no start freq. ≥ 2756 Hz showed a deficit
- Little concern for using NFC when start frequency is beyond the F2 range of most talkers (2067 – 2756 Hz)

When using low start frequencies be extra attentive to user’s progress and counsel user
- May need a period of acclimatization, even then, users might still do worse
Alexander (2012): Research Question

- Because the NFC start frequency and CR both influence how frequencies are remapped, there are infinite ways the unaidable high-frequency spectrum can be repackaged into the audible range of the listener
  - Lower start & lower CR vs. Higher start & higher CR

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Start Frequency

- **Hypothesis 1**
  - Lower start frequencies are detrimental for phonemes that rely heavily on formant frequency, especially vowels

- **Hypothesis 2**
  - Lower start frequencies are beneficial because
    - a) They allow a greater amount of high-frequency information to be lowered if CR is fixed
    - b) They allow for lower CRs (less reduction in spectral resolution) if the input bandwidth (the "max input" frequency) is fixed

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Compression Ratio

- **Hypothesis 1**
  - CR should be kept low to maintain spectral resolution of the lowered signal

- **Hypothesis 2**
  - CR should be increased so that a greater amount of high-frequency information can be lowered into the range of audibility

- **Hypothesis 3**
  - The optimal CR depends on start frequency
    - E.g., lower CRs might be best for low start frequencies, but less important for high start frequencies where formant frequencies are less critical

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Listeners

- **Group 1: Simulation of moderately-severe to profound high-frequency loss**
  - 14 (6 male, 8 female) listeners with sensorineural loss, ages 47-83 years (median = 70 years)

- **Group 2: Mild to moderate high-frequency loss**
  - 13 (6 male, 7 female) listeners with sensorineural loss, ages 27-82 years (median = 62 years)
Conditions

- 1 control condition with no NFC
- 6 experimental conditions with NFC
- All test conditions were low-pass filtered to the selected max output frequency
  - 3273 Hz (Group 1)
  - 4996 Hz (Group 2)
- A within-subjects, Latin Squares design was used

Can We Predict the Best Settings?

- Most manufacturers of frequency-lowering hearing aids recommend that the clinician adjust the setting based on the user’s perception of /s/-/ʃ/ via live voice
- Listeners participated in an additional 1-hour task that involved /s/-/ʃ/ discrimination for each of the NFC conditions
- The conditions that yielded best performance on this task did NOT predict the conditions that yielded best performance in the main experiment

Conclusions: Alexander (2012)

- Improvements in fricative/affricate identification should be expected when using NFC for a variety of hearing losses

Conclusions: Alexander (2012)

- Low start frequencies should be avoided
  - In cases where the bandwidth of audibility is restricted, it is better to tradeoff an increase in CR for a higher start frequency
  - In cases where the bandwidth of audibility is less restricted, attempts should be made to keep the start frequency above the range of most second formants

Conclusions: Alexander (2012)

- While CR reduces spectral resolution of the lowered signal, the important thing is where the compression occurs and not so much how much of it there is
  - When the start frequency is low, increasing CR decreases identification for vowels and non-fricative consonants
    - A slightly lower CR can be maintained by bringing less high-frequency information down into the range of audibility
    - However, if the reduction in high-frequency information is too great, fricative/affricate identification might not be optimized
  - For higher start frequencies, if sufficient high-frequency information is brought down, CR seems to be less important

Conclusions: Alexander (2012)

- Low start frequencies should be avoided
  - In cases where the bandwidth of audibility is restricted, it is better to tradeoff an increase in CR for a higher start frequency
  - In cases where the bandwidth of audibility is less restricted, attempts should be made to keep the start frequency above the range of most second formants
Conclusions: Alexander (2012)

- Attempts to identify the best NFC setting on an individual basis using a /s/-/ʃ/ discrimination task or rules that simply maximize input bandwidth are limited.

- Recommendations for selecting a setting also need to consider the start frequency, the CR, and the interaction between the two.

To Fit or Not to Fit

- **Conclusion for today**
  - There is not a lot of good evidence, period.
  - There is not a lot of evidence that existing techniques provide benefit beyond improving fricative identification.
  - There is some evidence that, when properly set, frequency lowering does not do harm.

- Ultimately, a decision has to be made whether the potential pros outweigh the cons.
  - If the decision is to fit, then there are a few things you should know about:
    - How the technology of choice works.
    - How much of lowered information the patient is getting (verification).

Be Your Own Best Guide

- General misunderstanding by clinicians about how the devices work and how to fit them.
- No standardized methods of fitting.
- Results might be highly individualized.

Special Verifit Test Signals

- "...four special versions of the Speech-std (1) test stimulus are provided in Speechmap to assist in the adjustment of frequency-lowering hearing aids. These are called Speech3150, Speech4000, Speech5000, and Speech6300. The Speech3150 stimulus has had the bands at 1000 Hz and above attenuated by 30 dB except for the 1/3 octave band at 3150 Hz which is unattenuated. [and so on]."

- (www.audioscan.com/resources/audiorepositories/audiorepositories/speechmap/speechmap.pdf)

FT Device 1000 Hz Start

- FT Device
- AE off
- AE (Basic)
- AE (Expanded)

No evidence of the transposed energy in the “expanded” mode.

Frye FONIX FP35 v6.12

- Presents a single (or double) tone to the hearing aid and graphs the entire frequency response.
SoundRecover Fitting Assistant

- Introduced May 2009, downloaded by audiologists in at least 20 different countries worldwide (not authorized by Phonak)
- Goal: maximize use of the audible bandwidth
- Uses a fuzzy logic model for selecting the optimal SoundRecover setting. Based on 4 variables:
  - Audible output bandwidth
  - Audible input bandwidth
  - Start frequency
  - Compression ratio
- For more information:
  - Video Tutorial: www.hearingseminars.com/p12364411
  - Slides: www.TinyURL.com/PurdueEAR (links to the above)

For your free copy, email: SRassist@gmail.com

SoundRecover “off”

Maximum Audible Output Freq.

Enter Preset Options

Family of Frequency I-O Curves

Settings for one audiogram from an actual CORE device

Max Audible Output

Input Frequency

For your free copy, email: SRassist@gmail.com
Identify the Optimal Setting

Setting B is chosen because it has a higher start, B provides 700 Hz more 'information' than A.

Optimal SoundRecover Setting

2.0 kHz start, 2:1:1

SR off
Optimal SR
Too Weak SR

Output is essentially identical to the optimal setting, yet has 700 Hz less information from the input.

Stronger SoundRecover Setting

1.7 kHz start, 2:1:1

SR off
Optimal SR
Too Weak SR

MPO and SoundRecover

1/3 Octave Bands

Expected Freq, Actual Freq.

Too Weak SoundRecover Setting

2.3 kHz start, 2:3:1

SR off
Optimal SR
Too Weak SR

Output is essentially identical to the optimal setting, yet has 700 Hz less information from the input.

Too Strong SoundRecover

1.5 kHz start, 3:2:3

SR off
Optimal SR
Too Strong SR

Under-utilized Audible BW
MPO Comparisons

1.5 kHz, 3.2:1
2.0 kHz, 2.2:1
SR off

Options:
- Maximize information for each ear independently
  - Potential for introducing conflicting information between ears
  - Perhaps best when large differences in audible bandwidth are due to large differences in hearing loss
- Select the same setting for both ears
  - Select a compromise between the two ears
  - Select the optimal setting for the better ear
  - Perhaps best when small differences in audible bandwidth are due to the fitting (e.g., feedback, insertion depth, RECD)

Binaural Fittings

Audiogram 1

Default is too strong

Audiogram 2

Default is too weak

Audiogram 3

Audibility Extender Fitting Assistant

Goal: choose the setting that
- Gives the most bandwidth ...
- with the least amount of overlap (highest start), ...
- and with no gaps ('holes') between un-transposed and transposed signals
- Adjust as necessary on follow up visits based on client perceptions
- Not authorized by Widex
- AudExtAssist@gmail.com
A Novel Way to Verify Frequency Shifting

- Using a 3.5mm male-male phono cord extension (6 ft. is preferable), the headphone jack from the Verifit is connected to the microphone jack on a standard computer.

- For a full demonstration and free downloadable software and test signal: www.TinyURL.com/PurdueEAR