# Detection of Word Final /s/ and /z/ with Three Modern Frequency Lowering Technologies

Krishna Rodemerk, Au.D., Jason Galster, Ph.D., Susie Valentine, Ph.D., Kelly Fitz, Ph.D.

Starkey Hearing Technologies

## Introduction

In the prescription of hearing aids, providing insufficient high-frequency gain may have a negative impact on detection of phonemes such as word final /s/ and /z/. Modern techniques for frequency lowering offer an opportunity for improving detection of these phonemes. In recent years three techniques for frequency lowering have been introduced to commercially available hearing aids. The first of these, introduced by the Widex Hearing Aid Company, uses linear frequency transposition (LFT) to lower high-frequency information above a specified start frequency to a lower frequency. Specifically, the algorithm identifies prominent spectral peaks in a frequency region up to two octaves above a specified start frequency. A frequency region of one octave around the identified spectral peak is filtered and transposed to a lower frequency region and mixed with the conventionally amplified lower frequencies.

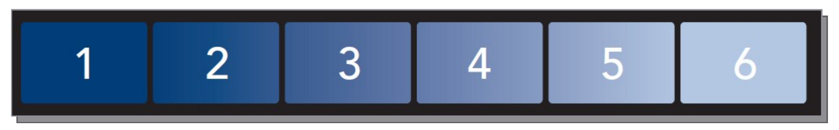


Figure 1. Illustrates a conventionally processed hearing aid. Each numbered box illustrates a hearing aid channel. Ranging from low-frequency (1) to high-frequency (6). Adapted from Simpson (2009).

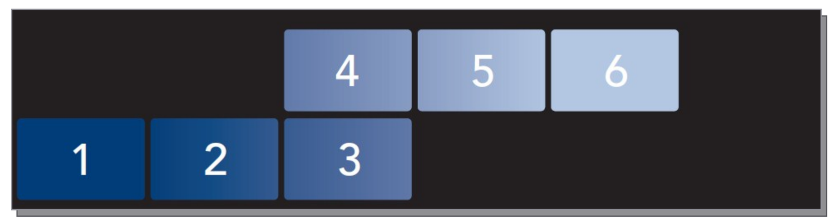


Figure 2. Illustrates the frequency lowering behavior of linear-frequency transposition. Adapted from Simpson (2009).

More recently, Phonak introduced a commercial hearing aid that features non-linear frequency compression (NLFC). This technique for frequency lowering moves high-frequency input to a lower frequency; this translation does not extend beyond a low-frequency cutoff that is defined within the programming software. Inputs above this cutoff are frequency compressed into a region specified by the frequency compression ratio; lower frequencies are compressed to a lesser extent than the highest frequencies.

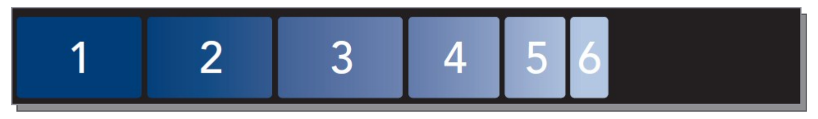


Figure 3. Illustrates the frequency lowering behavior of non-linear frequency compression . Adapted from Simpson (2009).

A third strategy for frequency lowering, spectral envelope warping (SEW), introduced by Starkey Hearing Technologies, uses a different approach to frequency lowering. High-frequency spectral peaks are identified by the algorithm; once identified, the envelope of this high-frequency information is estimated and replicated within a lower target frequency region. The newly introduced spectral envelope is mixed with the conventionally processed (CP) amplified pathway. The replicated stimulus cue is only presented while the corresponding high-frequency energy is present; otherwise the CP amplified pathway is maintained. All hearing aid output above 6 kHz is restricted when this algorithm is activated. The net effect of this behavior is an algorithm that was designed to identify high-frequency speech sounds such as /s/, /z/ or /ʃ/. Rather than lowering frequency regions that contain this energy, the spectral envelope of the high-frequency stimulus is replicated at a lower frequency, cuing the listener in to the presence of the high-frequency sound.

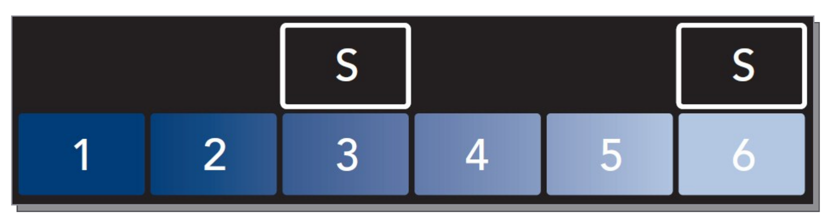


Figure 4. Illustrates the frequency lowering behavior of spectral envelope warping.

## Methods

**Objective**

The objective of the current study was to examine behavioral outcomes with three commercially available frequency lowering algorithms in a group of adults with sloping severe high-frequency hearing loss. The ability of this participant group to detect word final /s/ and /z/ sounds with broadband and bandlimited conventional processing was assessed and contrasted with the participants' ability to identify word final /s/ and /z/ with each of three frequency lowering algorithms activated. For reporting, each strategy was randomly assigned to a consistent identifier: A, B, or C.

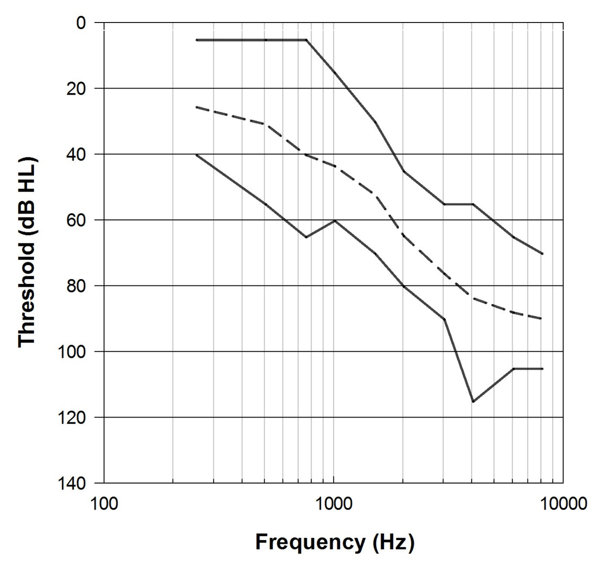


Figure 5 Average, maximum and minimum audiometric data for all participants are shown.

**Participants**

Twelve adults with sloping high-frequency hearing loss were recruited for participation in this study. All but one participant routinely wore hearing aids.

**Hearing aid products**

Commercially available behind-the-ear (BTE) hearing aids and programming software were used in this study: the Widex Mind440 M4-19 BTE, the Phonak Ambra SP BTE, and Starkey X Series Power BTE. All participants were fit with full shell custom earmolds; each earmold used a standard size 13 tube and clinically appropriate venting ranging from 1 to 3 mm.

**Verification**

Each hearing aid fitting was matched to DSL v5.0 adult targets within + 5 and - 10 dB through 4 kHz. Attempts to meet the 6 kHz DSL v5.0 target were made; however, in most cases, it was not possible to increase gain sufficiently to match target.

**Test Conditions (4)**

**1.) Broadband Conventional Processing**

**2.) Bandlimited Conventional Processing**

Conventionally processed hearing aid fitting with high-frequency gains at and above 4kHz reduced to the limits of the software. Intended to simulate manufacturer's first fittings.

**3.) Default Frequency Lowered**

Each frequency lowering algorithm is active. Adjustable parameters are left at the patient-specific manufacturer's defaults.

**4.) Validated Frequency Lowered**

The validation process was done with singular and plural stimuli randomly selected from the 'S-test' (Robinson et al., 2007). Participants identified each presented word as singular or plural. The variable parameters of each algorithm were made more aggressive until correct detection reached 60%.

## Methods

**Test Material**

Testing was done with the S-test as described by Robinson et al. (2007). In this test, 24 distinct pairs of words spoken by a female talker are randomly presented. Each word was presented twice: once in the singular form and once in the plural. The listener is tasked with detecting which form of the word was presented. Test presentation, randomization, scoring, and a graphical user interface were managed by a custom Matlab script. Participants were presented with one word from 0 degrees azimuth in soundfield at a calibrated level of 65 dB SPL. A steady-state background noise, shaped to the spectrum of the speech stimuli, was also presented from 0 degrees azimuth at a signal-to-noise ratio of +20 dB.

## Results

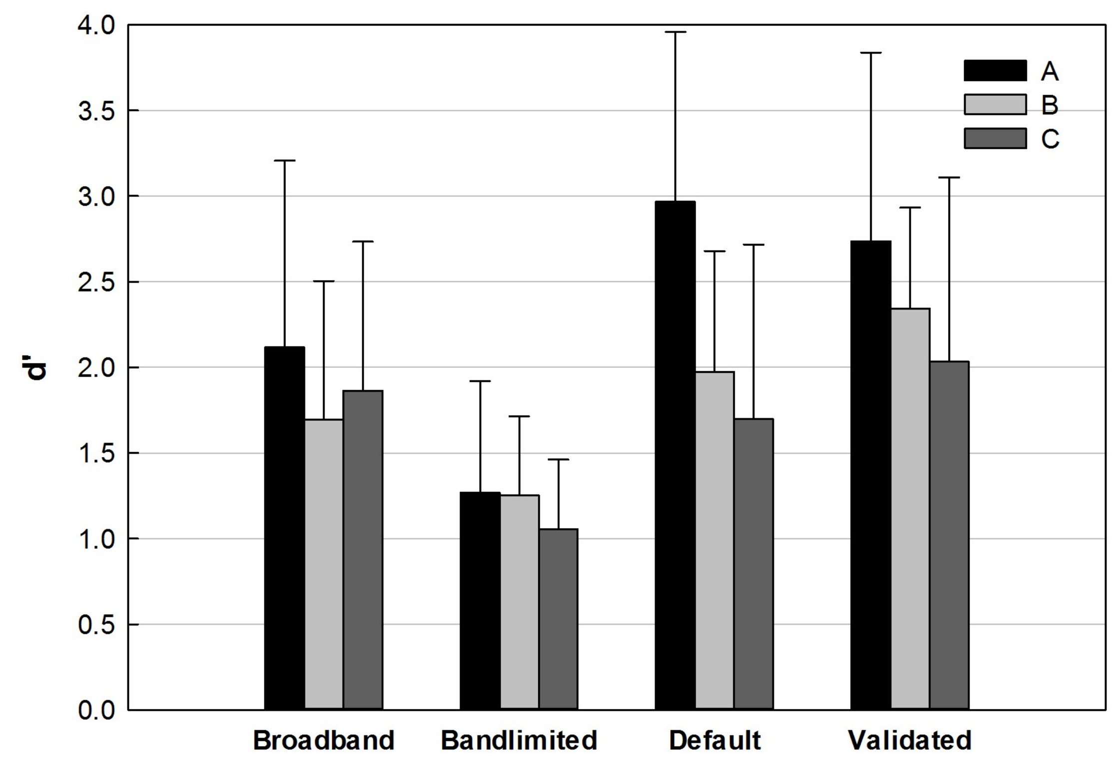


Figure 6. Average d' from the S-test are shown for each of three frequency lowering strategies and four test conditions. Error bars show +1 standard deviation.

**Results of Plural Detection**

- A two-factor repeated measures ANOVA showed a significant main effect of strategy ($F_{2, 22}$ = 12.640, $p$<0.001) and condition ($F_{3, 33}$ = 17.628, $p$<0.001). A significant interaction between strategy and condition ($F_{2, 6}$ = 3.021, $p$=0.011) was observed.
- Post-hoc analyses using pairwise multiple comparisons (Tukey Test) within the factor of strategy showed that strategy A offered significantly greater performance than both B ($p$=0.004) and C ($p$<0.001); strategies B and C were not significantly different.
- Analysis within the factor of test condition shows that bandlimiting a conventionally processed hearing aid response significantly decreases plural detection ($p$=0.002); performance in the default frequency lowered condition was significantly greater than conventionally processed bandlimited performance ($p$<0.001), but was not significantly better than broadband performance ($p$=0.278).

**Correlation between benefit of frequency lowering and high-frequency hearing loss slope**

- Correlations between individual benefit from each frequency lowering strategy and hearing loss slope were found to be non-significant. Analyses included slope calculated between 1 and 8 kHz; 4, 6 and 8 kHz; 6 and 8 kHz. The results of the analysis between 1 and 8 kHz are shown in the table below and figure 7.

| A vs. Slope | B vs. Slope | C vs. Slope |
|---|---|---|
| (r=-0.09, $p$=0.21) | (r=-0.02, $p$=0.52) | (r=-0.09, $p$=0.23) |

## Results

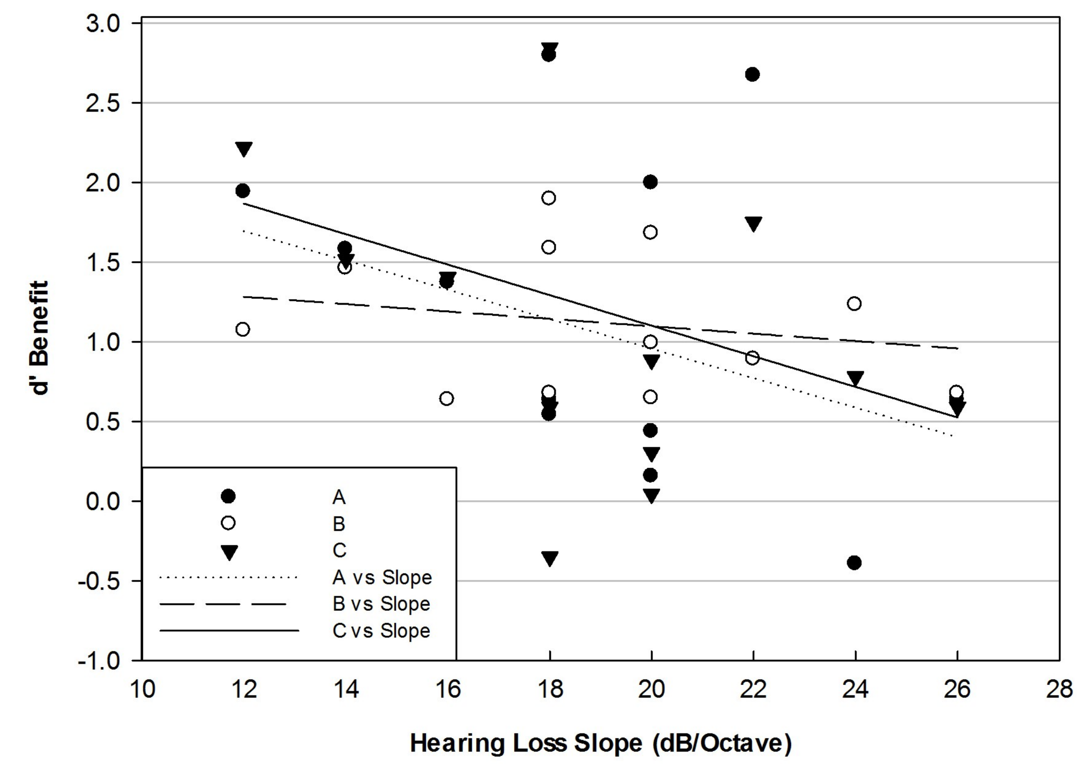


Figure 7. Benefit of frequency lowering is plotted as a function of hearing loss slope for each of three frequency lowering strategies. Benefit is the performance difference between the validated frequency lowered test condition and the conventionally processed bandlimited test condition. Hearing loss slope is calculated between 1 kHz and 8 kHz.

## Discussion

Even with advances in modern hearing aids there remain electroacoustic limitations that prevent restoration of audibility for high-frequency speech for individuals with severe to profound high-frequency hearing loss. As illustrated by an inability to meet prescribed DSL v5.0 adult targets for any of twelve participants beyond 4 kHz.

Three strategies for frequency lowering were evaluated and compared to conventionally processed test conditions. None of the evaluated frequency lowering strategies provided significant benefit for the detection of word final /s/ and /z/ when compare to a broadband hearing aid fitting that approximated each participant's DSL v5.0 prescription. Comparisons of performance in the frequency lowered test conditions to bandlimited conditions, representative of some clinical hearing aid fittings, revealed significant benefits for each of the strategies discussed.

No significant correlations were present between group or strategy and the magnitude of benefit received from frequency lowering. This suggests that benefit from frequency lowering, on the experimental task, does not hold a significant relationship to the slope or severity of hearing loss.

These observations should be considered in tandem with the acoustic fact that each strategy introduces distortion to the amplified signal. For some patients this additional distortion will not be acceptable. The prescription of frequency lowering should begin with a behavioral validation process that ensures improved detection of high-frequency sounds. Once a set of validated parameters have been determined the patient should be queried regarding acceptability of the resulting sound quality.

## References

Robinson, J.D., Baer, T., & Moore, B.C. (2007). Using transposition to improve consonant discrimination and detection for listeners with severe high-frequency hearing loss. *International Journal of Audiology, 46*, 293-308.

Simpson, A. (2009). Frequency-lowering devices for managing high-frequency hearing loss: A review. *Trends in Amplification*, *13*(2), 87-106.

**The authors would like to acknowledge the contributions of Buye Xu, Nazanin Nooraei, John Ellison, Drew Dundas, Zheng Yan, Harvey Abrams and Brent Edwards.**