# Digital noise reduction in hearing aids and its acoustic effect on consonants /s/ and /z/

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## ABSTRACT

**Introduction: Modulation-based noise reduction (MBNR) is one of the common noise reduction methods used in hearing aids. Gain reduction in high frequency bands may occur for some implementations of MBNR and fricatives might be susceptible to alteration, given the high frequency components in fricative noise. The main objective of this study is to quantify the acoustic effect of MBNR on /s, z/.**

**Methods: Speech-and-noise signals were presented to, and recorded from, six hearing aids mounted on a head and torso simulator. Test stimuli were nonsense words mixed with pink, cafeteria, or speech-modulated noise at 0 dB SNR. Fricatives /s, z/ were extracted from the recordings for analysis.**

**Results: Analysis of the noise confirmed that MBNR in all hearing aids was activated for the recordings. More than 1.0 dB of acoustic change occurred to /s, z/ when MBNR was turned on in four out of the six hearing aids in the pink and cafeteria noise conditions. The acoustics of /s, z/ by female talkers were affected more than male talkers. Significant relationships between amount of noise reduction and acoustic change of /s, z/ were found. Amount of noise reduction accounts for 42.8% and 16.8% of the variability in acoustic change for /s/ and /z/ respectively.**

**Conclusion: Some clinically-available implementations of MBNR have measurable effects on the acoustics of fricatives. Possible implications for speech perception are discussed.**

**KEY WORDS:**
*Modulation-based noise reduction; hearing aids; acoustic measures; fricatives*

## INTRODUCTION

Modulation-based noise reduction (MBNR) is one of the common noise reduction methods used in hearing aids.[1, 2] It is important to investigate the effects of MBNR on acoustics of fricatives because fricatives (specifically /s, z/) are important in spoken English and their acoustic characteristics are critical for listeners to recognise these speech sounds. Higher bandwidths are required by normal-hearing and hearing-impaired children than by adults for the perception of /s, z/ by female talkers.[3-7] In addition, fricatives might be susceptible to alteration by MBNR. In some hearing aids with MBNR, gain reduction in high frequency bands (2.0-9.0kHz) may occur[8] and could interfere with optimal audibility of /s, z/. When a speech-plus-noise signal is filtered into octave bands, the modulation depth of the signal decreases in the higher frequency region.[9] Given that fricative noise is mainly high frequency, its modulation depth will be reduced when the hearing aid processor filters the signal for further analysis. Because lower modulation depth is classified as noise by MBNR, this could lead to MBNR incorrectly classifying fricative noise as noise rather than a speech segment. Hence, gain reduction may occur for the hearing aid. The main goal in the present study was to investigate the effects of MBNR on the acoustic characteristics of /s, z/.

## MATERIALS AND METHODS

This study did not involve human subjects. Instead, six commercial behind-the-ear hearing aids from three manufacturers were included, chosen to represent a sample of the range that can be expected with clinical implementations of MBNR. The main characteristics of all hearing aids are listed in Table I. Some hearing aids had additional advanced features that were disabled where possible.

Speech-and-noise files of 90-second duration were used as test stimuli. Each file had 30 seconds of noise, followed by 30 seconds of speech-in-noise at 0 dB SNR, followed by 30 seconds of noise. The noise stimuli were steady-state pink noise, cafeteria noise, and speech-modulated International Collegium for Rehabilitative Audiology (ICRA) noise track number five.[10] The speech stimuli were nonsense words of four talkers from The University of Western Ontario Distinctive Feature Differences (UWO-DFD) test.[11] The speech and noise signals were mixed using an audio editor programme, Audacity 1.2.6., at 44.1kHz and 32-bit resolution. Three speech and noise files were created for each noise type and each of the four talkers: (a) speech plus noise, (b) speech plus phase-inverted noise, and (c) phase-inverted speech plus noise.

The target gain for each hearing aid was calculated based on a moderate to moderately-severe gently sloping (5dB per octave) sensorineural hearing loss that ranged from 40 to 65dB HL. The gain from 0.25 to 4.0kHz was verified using the Fonix 7000 hearing aid test system (Frye Electronics Inc., USA) to

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meet the Desired Sensation Level (DSLv5.0)[12] target gain for a 65 dB SPL speech input signal (within ± 3 dB). Software parameters used to generate the DSL targets included: (a) hearing aid type: behind-the-ear, (b) circuitry: wide dynamic range compression, (c) vent: no venting, (d) monaural fitting, (e) programme type: quiet, (f) verification signal: speech noise, (g) age of client: two years old, (h) transducer type: insert ear tip, (i) HL to SPL transform: average real ear to coupler difference. The compression ratio of all hearing aids was set to approximately 1:1 and verified at 0.5kHz, 1.0kHz, 2.0kHz, and 3.0kHz using the input-output curve measurement of the Fonix 7000 hearing aid test system (Frye Electronics Inc., USA). The compression ratios for each hearing aid were calculated over the input range 50-75dB SPL. Each hearing aid was programmed with two manual programmes in which MBNR was turned on to maximum in programme one and turned off in programme two. All other advanced features were disabled in both programmes. The maximum power output of all hearing aids was set to the maximum to avoid output limiting during the recordings.

Recordings were done in a double-walled sound-treated 8 X 8 foot booth, commonly used in audiometric testing. The noise floor was approximately 30dBA within the sound booth. Stimuli were stored on a computer with a CardDeluxe Soundcard with Audio Stream Input/Output (ASIO) drivers. Stimuli were routed from the computer to a MACKIE micro series 1202 twelve-channel microphone/line mixer for amplification, and presented in the sound treated booth via a Behringer Truth B203AS (Behringer USA Inc., Bothell, United States) loudspeaker. The position of the loudspeaker was fixed at 0° azimuth, one meter away from Knowles' Electronics Manikin for Acoustic Research (KEMAR). KEMAR was positioned in the center of the sound booth. Stimuli were presented to, and recorded from, one of six hearing aids mounted on a KEMAR type 45BA (G.R.A.S. Sound and Vibration, Denmark) with an artificial ear IEC 711 and a ½" pressure microphone Type 40AP. Each hearing aid was mounted on a pinna simulator and connected to the artificial ear with an earmold simulator. Recordings of the hearing aid output were routed from the microphone to the CCP Preamplifier to a CROWN d75A amplifier (CROWN Audio Inc., United States) via BNC cables and stored on the computer for offline analysis. Daily calibration ensured the overall stimulus root-mean-square level of 65 dB SPL (±3 dB) reached the hearing aid microphone. The recordings were digitized at a 44.1kHz and 32-bit resolution. The sequence of the hearing aids used in each recording session was counterbalanced.

The Inversion Technique[13] was used to separate speech from noise in the recordings for analysis. To allow the implementation of the inversion technique, sets of stimuli were recorded: (a) speech plus noise, (b) speech plus phase-inverted noise, and (c) phase-inverted speech plus noise. All stimuli within a set have the same spectral content; the only difference is that the noise waveform was inverted in (b) and the speech waveform was inverted in (c). For the first set of stimuli, we recorded (b) on Day-1 and (a) and (c) in Day-2 from all hearing aids. The recorded (a) and (b) files were mixed in Audacity to separate noise and speech post-recording for detailed acoustic analysis. The fact that the inversion technique was applied successfully to retrieve speech from the speech-plus-noise recordings suggests that the placement or fitting of the hearing aids on KEMAR ear has no effect on the recordings.

The segments /s, z/ were extracted from the retrieved speech file using Praat 5.1.11 (Boersma & Weenick, 2011) using pre-defined definitions of the segment boundaries that were verified through visual inspection of the spectrogram and auditory analysis to ensure that only the steady-state portion of the fricative was selected.

*Quantification of amount of noise reduction and effect of MBNR*
The efficacy of MBNR was quantified by the amount of noise reduction for each of the three noises. The amount of noise reduction was calculated by comparing level differences between two windows post-stimulus onset: 0.5 to 3.5second (before noise reduction activation) and 20.0 to 23.0second (well after noise reduction activation).

The effects of MBNR on the acoustics of /s, z/ were documented in terms of level difference across frequency when MBNR was on and off. A 22-band spectrum from 0.3kHz to 8.0kHz was generated for each token of /s, z/ from every recording, using Fast Fourier Transform with a 128 Hz Hanning window in Audacity. The level difference in any band that occurred more than 20dB below the peak level in the measured speech segment was given a weighting of "0" and thus did not contribute to the calculated difference. The level differences across frequency bands were summed and averaged and reported as the "average level difference (dB)."

## RESULTS

Noise reduction occurred in all hearing aids in the pink noise condition (range: 3.18 to 11.48dB) and in five hearing aids in the cafeteria noise condition (range: 1.50 to 5.06dB) when MBNR was activated. Less than 1.0dB of noise reduction (range: -0.98dB to 0.24dB) occurred in all hearing aids in the ICRA noise condition and in one hearing aid (0.18dB) in the cafeteria noise condition.

A total of 288 speech segments (six hearing aids X 2 phonemes X 2 hearing aid programs X 3 noises X 4 talkers) were extracted from the retrieved speech files and were analysed. Table II shows the average level difference (dB) for phoneme /s/ and /z/, processed by MBNR of six hearing aids, averaged between talker one and talker two for each talker gender. Positive numbers indicate enhancement, negative numbers indicate reduction, and values near zero indicate negligible difference. Shapiro-Wilk normality test showed that the normality assumption was violated for a few conditions: (i) female /s/ in cafeteria and ICRA noise and (ii) male /s/ and /z/ in cafeteria noise. Therefore, the non-parametric Wilcoxon Signed Rank test was conducted to compare the average level difference between male and female talkers in each noise condition.

In the pink noise condition, statistical results showed that there is a significant difference between female and male talkers for the average level difference of phoneme /s/ and /z/, [$Z = -2.21$, $p<0.05$]. Table II showed that four hearing aids had more than 1.0dB of average reduction for the phoneme /s/ spoken by the female and male talkers. Five hearing aids

**Table I: Hearing aid features and settings**

| HA code | Number of processing channels | NR algorithm | Number of channels | NR setting | | Compression Ratio | | | | Maximum Power Output (dB SPL) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Program 1 | Program 2 | 0.5 kHz | 1 kHz | 2 kHz | 3 kHz | 0.5 kHz | 1 kHz | 2 kHz | 3 kHz |
| HA1 | 7 | MBNR | 8 | Maximum (10 dB NR) | Off | 1.5 | 1.4 | 1.5 | 1.5 | 102.4 | 108.1 | 113.0 | 115.1 |
| HA2 | 6 | MBNR | 6 | Maximum (strong) | Off | 1.1 | 1.1 | 1.2 | 1.2 | 107.8 | 113.2 | 117.0 | 113.9 |
| HA3 | 20 | MBNR | 20 | Maximum (strong) | Off | 1.3 | 1.3 | 1.4 | 1.3 | 107.0 | 111.2 | 116.2 | 114.4 |
| HA4 | 16 | MBNR | 16 | Maximum (strong) | Off | 1.1 | 1.1 | 1.3 | 1.2 | 106.8 | 111.1 | 116.7 | 114.5 |
| HA5 | 4 | MBNR | 4 | On (up to 9 dB NR) | Off | 1.0 | 0.9 | 0.9 | 1.0 | 117.0 | 123.3 | 128.0 | 120.0 |
| HA6 | 16 | MBNR + Wiener filter | 16 | Maximum (12-24 dB NR) | Off | 1.0 | 1.0 | 1.0 | 1.0 | 113.8 | 120.9 | 120.9 | 118.5 |

Note: NR=noise reduction; HA=hearing aid; MBNR=modulation-based noise reduction.

**Table II: Average level difference (dB) for phoneme /s/ and /z/**

| Test Conditions | Phoneme /s/ | | | | | | | Phoneme /z/ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HA1 | HA2 | HA3 | HA4 | HA5 | HA6 | Mean (SD) | HA1 | HA2 | HA3 | HA4 | HA5 | HA6 | Mean (SD) |
| Pink Noise | | | | | | | | | | | | | | |
| • Female | 0.49 | -3.69 | -3.82 | -2.61 | 0.07 | -5.86 | -2.57 (2.45) | -0.69 | -5.28 | -5.91 | -4.46 | -1.12 | -5.23 | -3.78 (2.28) |
| • Male | 0.60 | -1.15 | -1.07 | -1.23 | 0.15 | -3.87 | -1.10 (1.56) | -0.17 | -0.95 | -0.50 | 0.42 | 0.06 | -2.51 | -0.61 (1.04) |
| Cafeteria Noise | | | | | | | | | | | | | | |
| • Female | -0.07 | -1.29 | -1.89 | -0.86 | 0.31 | -5.86 | -1.61 (2.23) | -0.30 | -2.64 | -3.59 | -2.51 | -0.25 | -4.48 | -2.30 (1.72) |
| • Male | 0.17 | -0.48 | -0.12 | -0.53 | 0.30 | -4.00 | -0.78 (1.61) | -0.15 | 0.15 | 0.08 | 0.53 | 0.15 | -2.92 | -0.36 (1.27) |
| ICRA Noise | | | | | | | | | | | | | | |
| • Female | 2.13 | -0.61 | -0.22 | 0.42 | -0.13 | -0.13 | 0.24 (0.98) | -0.16 | -0.82 | -0.61 | -0.16 | -0.05 | -1.15 | -0.49 (0.44) |
| • Male | 0.02 | -0.22 | 0.20 | 0.10 | 0.03 | -0.16 | -0.01 (0.16) | -0.17 | -0.10 | 0.23 | 0.56 | 0.05 | -0.44 | 0.02 (0.35) |

had more than 1.0 dB of average reduction for female talkers and one hearing aid had more than 1.0 dB of average reduction for male talkers /z/.

In the cafeteria noise condition, statistical results showed that there is a significant difference between female and male talkers for the average level difference of phoneme /s/ and /z/ (Z = -1.99, $p<0.05$). Table II shows that three hearing aids had more than 1.0 dB of average reduction for female talkers and one hearing aid had more than 1.0 dB of average reduction for male talkers /s/. Four hearing aids had more than 1.0 dB of average reduction for female talkers and one hearing aid had more than 1.0 dB of average reduction for male talkers /z/.

In the ICRA noise condition, statistical results showed that there is a significant difference between female talker and male talker for the average level difference of phoneme /z/ (Z= -2.00, $p<0.05$); but there is no significant difference for phoneme /s/ (Z = -0.11, $p>0.05$). Table II shows only one hearing aid had more than 1.0 dB of average reduction for male talkers.

The correlation between amount of noise reduction and acoustic change was examined. Kolmogorov-Smirnov normality test showed that none of the variables of amount of noise reduction, average level difference for /s/, and average level difference for /z/ met the assumption of normality for parametric analysis; therefore, Spearman correlation was conducted. There was a significant relationship between amount of noise reduction and acoustic change of /s/, r = -0.662, $p<0.01$. There was a significant relationship between amount of noise reduction and acoustic change of /z/, r = -0.410, $p<0.01$.

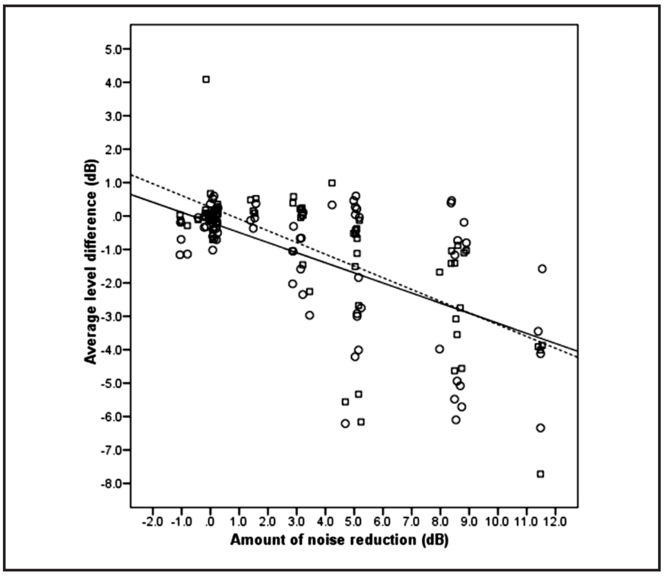


**Fig. 1:** Scatter plot of average level difference for consonant /s/ (squares) and /z/ (circles) as a function of amount of noise reduction. The dotted line represents the linear plot of /s/ average level difference as a function of amount of noise reduction, R2=0.428. The dark line represents the linear plot of /z/ average level difference as a function of amount of NR, R2=0.168.

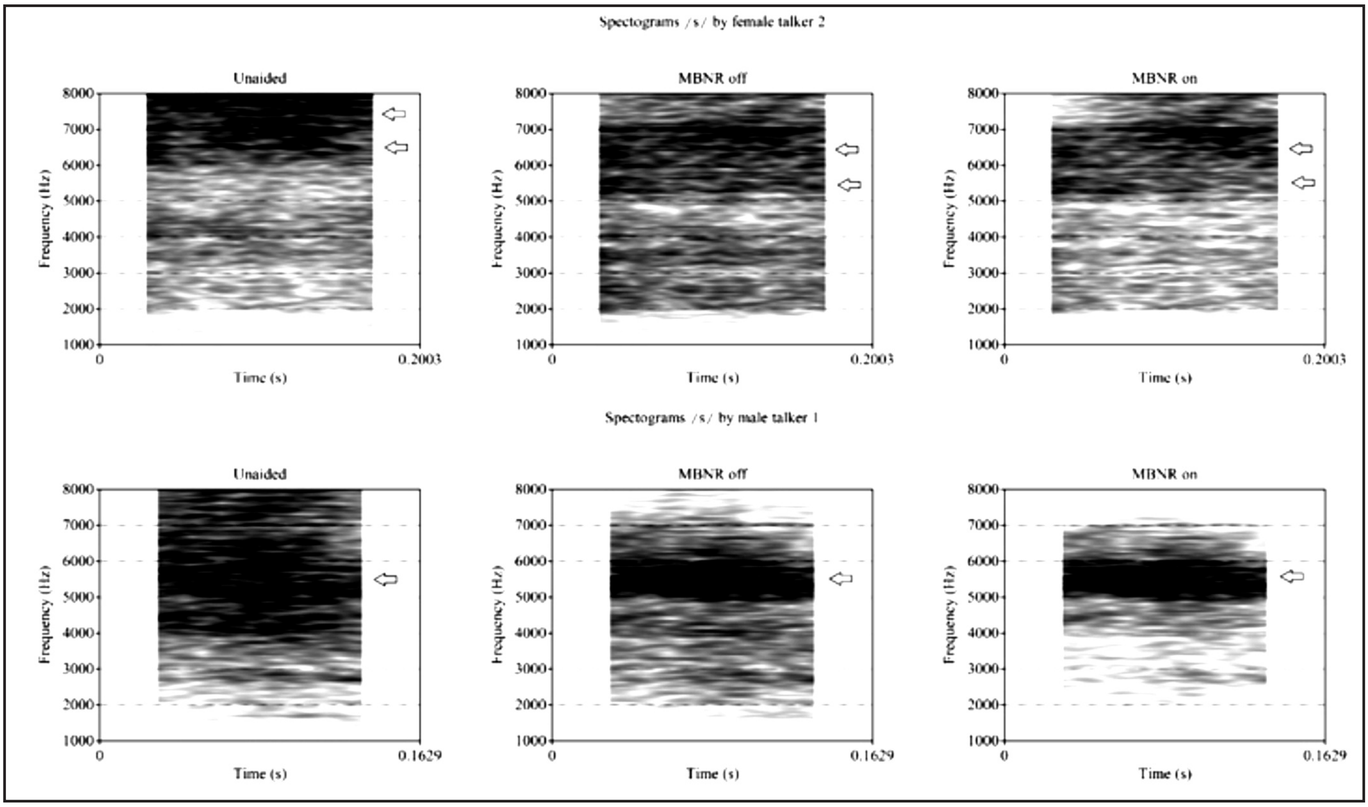


**Fig. 2:** Spectrograms of /s/ unaided and pre- and post-processing by modulation-based noise reduction of HA4. Darker shade in the spectrograms indicates higher energy concentration. The arrows indicate frequency region with highest energy.

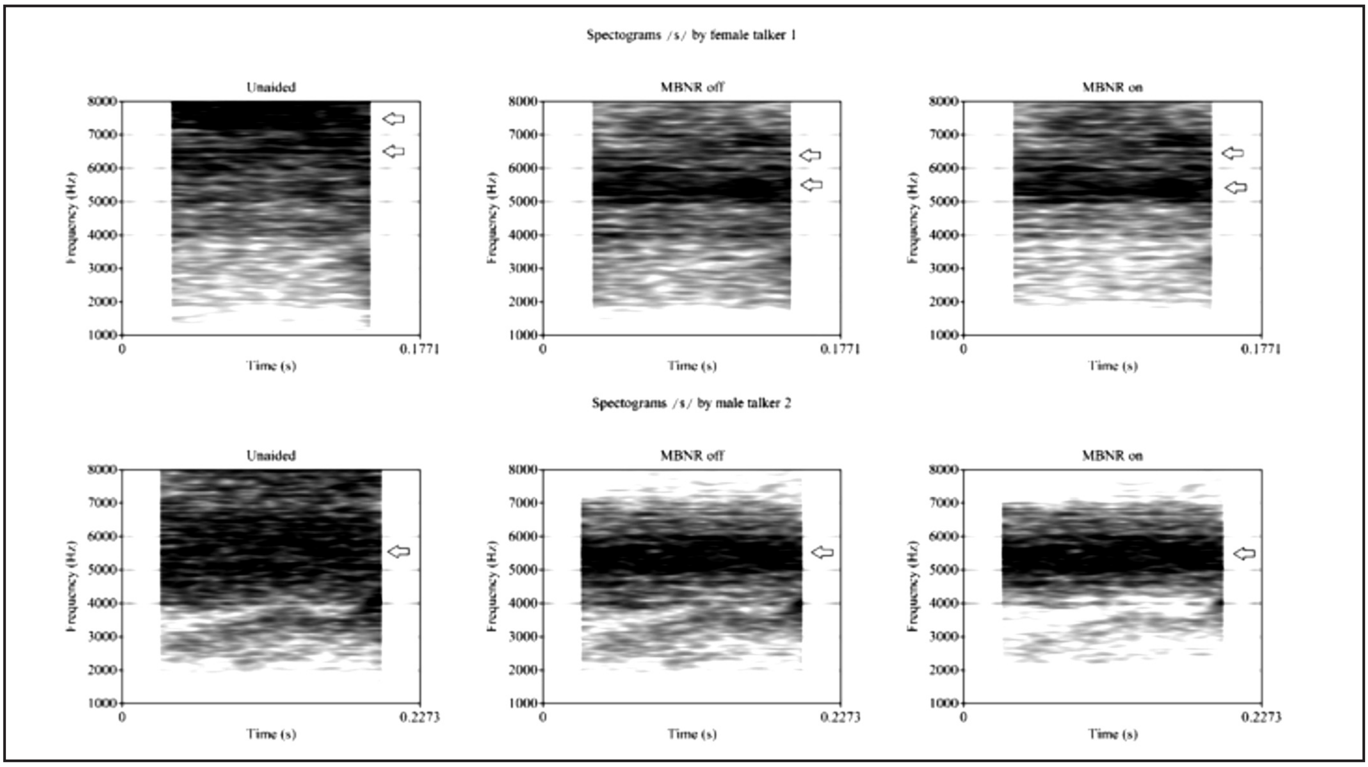


**Fig. 3:** Spectrograms of /s/ unaided and pre- and post-processing by modulation-based noise reduction of HA2. Darker shade indicates higher energy concentration. The arrows indicate frequency region with highest energy.

Figure 1 shows the average level difference for consonant /s/ (squares) and /z/ (circles) as a function of amount of noise reduction. The results showed that the amount of noise reduction accounts for 42.8% and 16.8% of the variability in acoustic change for /s/ and /z/, respectively.

To help illustrate the acoustic change after MBNR, the spectrographic patterns of the frication noise portion obtained from two representative hearing aids were analysed. We chose hearing aids with average level differences that were close to the mean change (see Table II). Figure 2 and 3 show the spectrograms of frication noise portion of /s/ extracted from pink noise using the inversion technique under the unaided, aided MBNR-off, and aided SMNR-on conditions, for HA4 and HA2, respectively. The left, middle, and right panels show the spectral difference between /s/, spoken by a female and male talker, prior to hearing aid processing, after hearing aid processing with MBNR deactivated, and after hearing aid processing with MBNR activated, respectively. Darker shades in the spectrograms represent higher energy at the frequency regions shown in the y-axis. Note that the spectrum of /s/ for the female talker is higher than the /s/ of the male talker in the unaided condition, as indicated by the darker shade between 6000Hz to 8000Hz. The middle panels in Figure 2 and 3 show the reduction of high frequency energy in fricative noise, particularly for /s/ spoken by the female talker, when processed by these hearing aids: the high frequency energy was shifted from the 6.0 to 8.0kHz region to the 5.0 to 7.0kHz region. When MBNR was activated (see Figure 2 upper right panel), the 5.0 to 7.0kHz region remained prominent.

The energy concentration for male fricative noise at 5.0kHz to 6.0kHz remained prominent between the two aided conditions.

## DISCUSSION

The aim of the current study is to examine the acoustic effects of noise reduction in hearing aids on noise-like consonants such as fricatives /s/ and /z/. The results showed that more than 1.0 dB of acoustic change occurred to /s, z/ when MBNR was turned on in four out of the six hearing aids in the pink and cafeteria noise conditions. The amount of average level reduction was higher for female talkers than male talkers in the pink and cafeteria noise conditions. Although there is a moderate correlation between amount of noise reduction and acoustic change, the former does not account for all the variability in the latter. However, a greater amount of noise reduction is likely to affect the acoustics of /s, z/ more. It should be noted that using the average value for acoustic change would miss some important spectral changes. Alternative ways to characterized spectral changes can be done by measuring spectral moments (e.g., spectral mean, variance, skewness, and kurtosis) of fricatives and affricates with and without MBNR processing.[14]

The interpretations of the middle panels in Figure 2 and 3 are consistent with previous research showing that hearing aids may reduce the bandwidth of amplified /s/.[15] Given the importance of audibility and bandwidth of fricatives for young children,[3-7,16] the shift in the high energy bandwidth could affect the audibility of /s/ and discrimination between /s/ and /ʃ/ (with a lower spectral mean). However, the right panels in Figure 2 and 3 shows that MBNR resulted in only subtle changes to the aided spectra of fricative /s/, where the 5.0 to 7.0kHz region remained prominent. Because no behavioural measurement has been conducted within this study, it is beyond the aim and scope of the current study to conclude whether the acoustic changes documented here will have an effect on the perception of /s, z/. Therefore, future studies need to examine audibility of fricatives processed with and without MBNR and define meaningful amount of acoustic changes that will cause a perceptual change.

## CONCLUSION

Some clinically-available implementations of MBNR have measurable effects on the acoustics of fricatives. However, the perceptual consequences of the acoustic effects found in this study is unknown. Future research is required to measure the relationship between the acoustic changes obtained in this study and effects on perception of fricatives.

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## REFERENCES

1. Bentler R, Chiou LK. Digital noise reduction: an overview. Trends Amplification. 2006; 10(2): 67-82.
2. Chung K. Challenges and recent developments in hearing aids. Part I. Speech understanding in noise, microphone technologies and noise reduction algorithms. Trends Amplification. 2004; 8(3): 83-124.
3. Kortekaas RW, Stelmachowicz PG. Bandwidth effects on children's perception of the inflectional morpheme /s/: acoustical measurements, auditory detection, and clarity rating. J Speech Lang Hear Res. 2000; 43(3): 645-60.
4. Pittman AL, Stelmachowicz PG. Perception of voiceless fricatives by normal-hearing and hearing-impaired children and adults. J Speech Lang Hear Res. 2000; 43(6): 1389-1401.
5. Stelmachowicz PG, Nishi K, Choi S, Lewis DE, Hoover BM, Dierking D, et al. Effects of stimulus bandwidth on the imitation of ish fricatives by normal-hearing children. J Speech Lang Hear Res. 2008; 51(5): 1369-80.
6. Stelmachowicz PG, Pittman AL, Hoover BM, Lewis DE. Aided perception of /s/ and /z/ by hearing-impaired children. Ear Hear. 2002; 23(4): 316-24.
7. Stelmachowicz PG, Pittman AL, Hoover BM, Lewis DE. Effect of stimulus bandwidth on the perception of /s/ in normal- and hearing-impaired children and adults. J Acoust Soc Am. 2001; 110(4): 2183-90.
8. Hoetink AE, Korossy L, Dreschler WA. Classification of steady state gain reduction produced by amplitude modulation based noise reduction in digital hearing aids. Int J Audiol. 2009; 48(7): 444-55.
9. Schum DJ. Noise-reduction circuitry in hearing aids: (2) goals and current strategies. Hear J. 2003; 56(6): 32-40.
10. Dreschler WA, Verschuure H, Ludvigsen C, Westermann S. ICRA noises: artificial noise signals with speech-like spectral and temporal properties for hearing instrument assessment. International Collegium for Rehabilitative Audiology. Audiology. 2001; 40(3): 148-57.
11. Cheesman MF, Jamieson DG. Development, evaluation and scoring of a nonsense word test suitable for use with speakers of Canadian English. Can Acoust. 1996; 24(1): 3-11.
12. Scollie S, Seewald R, Cornelisse L, Moodie S, Bagatto M, Laurnagaray D, et al. The Desired Sensation Level multistage input/output algorithm. Trends Amplification. 2005; 9(4): 159-97.
13. Hagerman B, Olofsson Å. A method to measure the effect of noise reduction algorithm using simultaneous speech and noise. Acta Acustica United with Acustica. 2004; 90(2): 356-61.
14. Jongman A, Wayland R, Wong S. Acoustic characteristics of English fricatives. J Acoust Soc Am. 2000; 108(3 Pt 1): 1252-63.
15. Boothroyd A, Medwetsky L. Spectral distribution of /s/ and the frequency response of hearing aids. Ear Hear. 1992; 13(3): 150-7.
16. Stelmachowicz PG, Pittman AL, Hoover BM, Lewis DE, Moeller MP. The importance of high-frequency audibility in the speech and language development of children with hearing loss. Arch Otolaryngol Head Neck Surg. 2004; 130(5): 556-62.