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Kertas Asli/*Original Articles*

The Electroacoustic Performance of Digital Noise Reduction Systems in Commercial Hearing Aids with Malay Speech-Plus-Noise Test Signals
(Prestasi Elektroakustik Sistem Pengurangan Hingar Digital dalam Alat Bantu Pendengaran Komersial dengan Isyarat Ujian Pertuturan-Dalam-Bising Bahasa Melayu)

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ABSTRACT

One of the most frequent complaints of individuals with hearing impairment is listening comfort in noisy environments. In order to improve listening comforts in background noise, digital noise reduction (DNR) systems are incorporated into hearing aids (HAs). Each hearing aid manufacturer has its proprietary algorithm for the DNR system. The amount of attenuation (dB) provided by the DNR system can be quantified using the hearing aid analyser. However, the standard test signals in the hearing aid analyser could not quantify the attenuation of DNR for speech mixed with noise signals. Therefore, this study aimed to (i) develop speech-plus-noise test signals that incorporate Malay sentences and (ii) quantify the efficacy of DNR systems in commercial hearing aids using the newly developed test signals. Six different brands of hearing aids with identical technology but from different manufacturers were subjected to electroacoustic testing utilising newly created Malay speech-in-noise test signals with and without DNR enabled. The total root-mean-square (RMS) gain reduction for each HA was calculated. The results show that the types of noise, the signal-to-noise ratio and the gender of the speaker have a significant effect ($p<0.05$) on the amount of gain reduction in the HA output as a result of the DNR system in each HA . In conclusion, the newly developed Malay speech-in-noise test signals can be used to verify the efficacy of DNR system in commercial hearing aids.

Keywords: Digital noise reduction, Signal-to-noise-ratio, Hearing aids, Electroacoustic testing

ABSTRAK

Masalah dalam bising merupakan satu aduan paling biasa bagi individu bermasalah pendengaran. Oleh itu, bagi meningkatkan keselesaan mendengar dalam bunyi bising, sistem pengurangan hingar digital (DNR) telah diperkenalkan ke dalam alat bantu pendengaran (ABP). Setiap pengeluar ABP mempunyai algoritma sistem DNR yang tersendiri. Jumlah pengurangan (dB) yang diberikan oleh sistem DNR boleh diukur menggunakan penganalisis ABP. Walau bagaimanapun, signal ujian standard dalam penganalisis ABP tidak dapat mengukur prestasi DNR untuk signal pertuturan yang bercampur dengan hingar. Oleh itu, kajian ini bertujuan untuk (i) membangunkan signal ujian pertuturan-dalam-bising dalam bahasa Melayu dan (ii) mengukur keberkesanan sistem DNR dalam ABP komersial menggunakan signal ujian pertuturan-dalam-bising yang baru dibangunkan tersebut. Enam jenama alat bantu pendengaran berbeza dengan teknologi yang sama tetapi daripada pengeluar berbeza telah menjalani ujian elektroakustik menggunakan signal ujian pertuturan-dalam-bising dalam bahasa Melayu tersebut dengan dan tanpa DNR diaktifkan. Jumlah pengurangan gandaan punca-min-kuasa dua (RMS) bagi setiap ABP telah dikira. Keputusan menunjukkan bahawa jenis hingar, nisbah signal kepada hingar dan jantina penutur mempunyai kesan yang signifikan ($p<0.05$) ke atas jumlah pengurangan keuntungan dalam output HA hasil daripada sistem DNR dalam setiap HA . Kesimpulannya, isyarat ujian pertuturan dalam bahasa Melayu yang baru dibangunkan boleh digunakan untuk mengesahkan keberkesanan sistem DNR dalam alat bantu pendengaran komersial.

Kata kunci: Pengurangan hingar digital, Nisbah signal-kepada-hingar, Alat bantu pendengaran, Ujian elektroakustik

INTRODUCTION

Difficulty understanding speech in the presence of noise has been one of the most prevalent complaints of hearing-impaired individuals (Healy & Yoho 2016). Despite the availability of technologies such as hearing aids to assist in this circumstance, the lack of speech clarity in noise has been the primary deterrent for many potential hearing aid users (Kochkin, 2007). The problem is exacerbated when the noise is speech-like, such as multi-talker babble noise because the multi-talker babble noise overlaps spectrally better than, e.g. a white noise with the intended speech signals, consequently reducing the intelligibility (Gundmi et al. 2018).

In recent years, digital hearing aids technology has made tremendous advancements toward better speech recognition and sound clarity. It opens up substantial new possibilities to overcome various hearing difficulties. Intriguingly, modern signal processing technologies, particularly the digital noise reduction (DNR) system in most current commercial digital hearing aids, address various amplification needs and enhance user satisfaction (Wu et al. 2019). DNR system is implemented in hearing aids to reduce listening effort and improve listening comfort, sound quality, and potentially, understanding of speech in noise (Brons et al. 2013; Desjardins 2016; Desjardins & Doherty 2014; Eddins et al. 2013). In order to achieve these goals, the DNR system needs to distinguish noise-dominated components from speech-dominated components within an incoming signal and estimate the signal-to-noise ratio (SNR) of that signal. Subsequently, gain reduction is applied to the noise-dominated signals.

The amount of attenuation provided by DNR in the HA output when noise is present varies with a set of pre-determined gain-decision rules or algorithms. Different DNR systems have different algorithm approaches in terms of signal detection methods, decision rules, and time constants (Chung 2004). Currently, there are several proprietary DNR algorithms, such as modulation-based noise reduction (MBNR), synchrony detection and spectral subtraction (Chong & Jenstad 2018a). The modulation-based noise reduction (MBNR) is also known as adaptive multichannel noise reduction. MBNR detects the presence of speech when the estimated modulation depth of a signal is 15 dB or more, and its modulation rate is between 3 and 10 Hz (Chong & Jenstad 2018a; Schum 2003). Environmental noises are often unmodulated or have modulation rates outside this range. The synchrony detection algorithm uses a speech detector to detect harmonic features in a signal to indicate the presence of speech (Bentler & Chiou 2006; Chong & Jenstad 2018; Chung 2004; Powers & Beilin 2013; Schum 2003). The spectral subtraction algorithm estimates the noise spectrum during pauses in speech and the presence of speech is detected by a voice activity detector (Neher et al., 2015). It estimates the noise spectrum when the speech signal is not present and then subtracts the noise spectrum from the noisy speech signal to obtain a clean speech signal spectrum. The MBNR, synchrony detection, and spectral subtraction algorithms can be implemented as a single system or in a combination of systems within a hearing aid.

Despite the differing approaches, studies on the effects of DNR systems in commercial HAs tend to show mixed results. On one hand, several studies showed no significant positive or negative effect of DNR on speech recognition. For example, studies that examined the MBNR algorithm found no significant difference in speech recognition performance when DNR was turned on or off (Alcántara et al., 2003; Bentler et al, 2008; Boymans & Dreschler 2000; Marcoux et al. 2006; Walden et al. 2006; Zakis et al. 2009). Studies that examined (i) a combination of MBNR and Wiener filtering algorithm in Siemens hearing aids and (ii) spectral subtraction algorithm in Starkey HAs also showed similar results (Desjardins 2016; Desjardins & Doherty 2014; Lowery & Plyler 2013; Mueller et al. 2006; Ricketts & Hornsby 2005). On the other hand, several studies that examined the DNR system in Widex HAs, known as the speech enhancer algorithm, showed a significant improvement in speech recognition when DNR was turned on (Kuk et al. 2011; Peeters et al. 2009).

The discrepancies in these studies can be attributed to the proprietary algorithms and the test signals used. Hoetink et al. (2009) showed that DNR systems of different hearing aids could have different amounts of gain reduction despite the same stimulus being used to examine the MBNR. The rules applied to DNR are unique to each manufacturer. Manufacturers' DNR systems may vary in terms of the SNR, weight of the importance of the speech frequencies, timing strategies, and noise classification. The noise classification differences will affect all DNR properties for that hearing aid. Therefore, the amount of gain reduction of one hearing aid cannot be generalized to all hearing aids. To date, no study has shown a relationship between the amount of gain reduction and speech perception in noise using the same test signals, partly because the stimuli available in a hearing-aid analyser to test DNR system only contain noise signals, whereas speech perception in noise is tested using speech-plus-noise signals. However, the DNR-on setting was mainly preferred by the participants over the DNR-off setting in reducing listening effort (Desjardins 2016; Desjardins & Doherty 2014).

Nevertheless, the majority of test signals in hearing aid analysers or test box systems are noise. A hearing aid analyser is a sound-treated box that permits precise and reproducible measurements of hearing aids. There are several brands of hearing-aid analyser but generally, it consists of an anechoic chamber, a loudspeaker, a reference microphone, a measurement microphone, and a 2cc-coupler with HA-1 or HA-2 adapters.

Scollie et al. (2016) have shown that using noise-only test signals may overestimate the efficacy of the DNR system where the amount of attenuation produced by a DNR system within a hearing aid differed when tested with noise-only signals (21 dB of attenuation) as compared to speech-plus-noise signals (15 dB of attenuation). In addition, Chong & Jenstad (2018b) showed that DNR systems may affect noise-like speech sounds when tested with speech-plus-noise signals. Therefore, it would be ideal to have speech-in-noise stimuli to test the efficacy of DNR in a test box and to have the same stimuli for testing speech perception in noise among hearing aid users, so that the correlation between objective measurement (i.e., electroacoustic measurement) and subjective measurement (i.e., speech perception in noise) can be established in future studies. Currently, test signals used in a HA analyser are rarely used to test speech perception among hearing aid users. It is known that the International Speech Test Signal (ISTS; Holube et al., 2010) is one of the current test signals available for hearing aid measurements. However, the measurement outcomes such as electroacoustic results and speech perception performance are incomparable and challenging to discuss.

The Malay language is the official language in Malaysia and it is spoken as native language by at least 80% of the population in Malaysia. However, most studies examining the effects of DNR systems on speech perception have used English test materials. Kilman (2015) stated that using one's native language is crucial when assessing speech perception performance. Warzybok et al. (2015) also indicated that it is important to test subjects in their native language because the performance of non-native listeners will depend on the complexity of speech materials and they cannot use context as efficiently as native listeners. Besides, experiment data test with different languages provided can be used to compare with each other in order to provide equal standards of diagnostic and hearing aids prescription (Hochmuth et al. 2015).

Thus, this study aimed to develop speech-plus-noise test signals that incorporate Malay sentences and examine the DNR's efficacy (i.e., amount of gain reduction in noise) in current commercial hearing aids. Current hearing-aid analysers offer noise signals for quantifying the amount of attenuation (dB) provided by DNR. However, these test signals could not quantify the attenuation of DNR for speech mixed with noise signals. Therefore, this study aimed to (i) develop speech-plus-noise test signals that incorporate Malay sentences language and (ii) quantify the efficacy of the DNR systems in commercial hearing aids using the newly developed test signal.

METHODS

DEVELOPMENT OF TEST SIGNALS.

The purpose of this part is to develop Malay speech-plus-noise test signals for use in Part 2. Malay language or Bahasa Malaysia is the official national language and it is spoken by over 80% of the population (Article 152 of the Constitution of Malaysia). Audacity (version 2.4.2; Audacity Team), a free and open-source sound editing software, was used to create the speech-plus-noise test signals. The same sentence list from The Malay Hearing in Noise Test (MyHINT; Quar et al. 2008) was utilised to develop a speech-plus-noise signal with different talkers (male and female), noise types (white noise and multi-talker babbling noise), and SNR levels (0, +5, and +10 dB SNR).

The sentence lists from MyHINT (Quar et al. 2008) were used for the speech stimuli. The sentences were recorded by two Malay native speakers (male and female). An example of a sentence is "*Pinggan itu jatuh ke lantai* (English translation "the plate fell to the ground)". All recordings were saved at a sampling rate of 44.1 kHz and 16 bits for offline editing. The sentences were equalised to the same root-mean-square (RMS) voltage level.

White noise was generated using the Audacity software. To create the multi-talker babble noise, three male and three female volunteers were recruited to read an unrelated article in Malay. Their readings were recorded individually but later were mixed to create the multi-talker babble noise. The white noise and the babble noise were equalised to the required RMS voltage to create different SNR (0, +5, +10 dBSNR) when mixed with the speech signals to create the speech-plus-noise test signals. The test signal consisted of 10 seconds of noise stimulus followed by a 10-second sentence-plus-noise signal. The 10 seconds of noise preceding the speech ensured that the DNR was fully activated before delivering the speech signals in noise.

ELECTROACOUSTIC ANALYSIS

The measurement set-up includes a computer that connected to a Audioscan Verifit Hearing Instrument Analyser RM500 SL (Etymonic Design Incorporation, Ontario, Canada), which consists of an anechoic chamber, a loudspeaker, a reference microphone, a measurement microphone, and a 2cc-coupler with HA-1 and HA-2 adapters. The hearing aids were placed in the hearing aid analyser. The hearing aid's ear hook was connected to the 2-cc coupler via a plastic tubing on the HA-2 adapter. The hearing aid's microphone was placed close to the reference microphone in the hearing aid analyser. Six brands of behind-the-ear (BTE) hearing aids (Table 1) were tested under different test conditions. Hearing aids with almost similar channels were selected for this study.

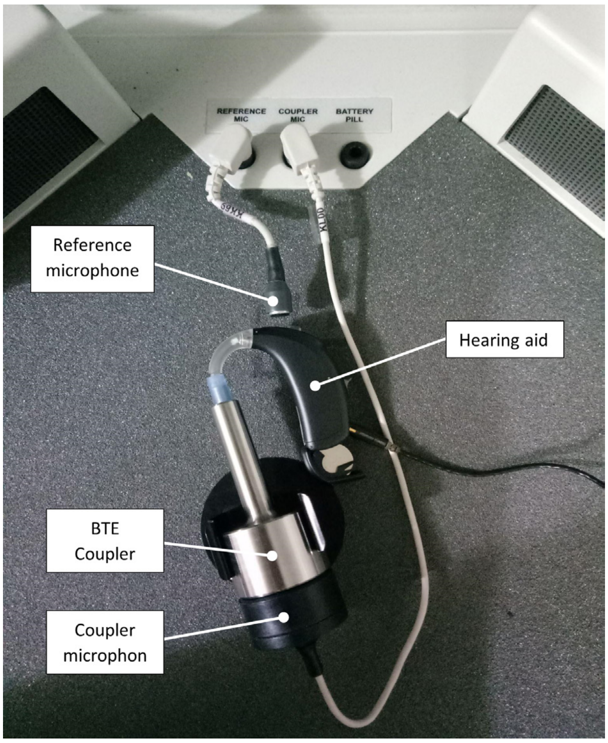

Figure 1. Setup for electroacoustic testing

Table 1. Six brands of hearing aids used in the study, with an almost similar number of channels and their type of digital noise reduction algorithm.

Brand	Type	Type of DNR algorithm	Number of channels
Widex	Unique 440	Modulation-based	15
Signia	Motion 2 px	Modulation-based	16
Starkey	Muse i1600	Modulation-based	16
Phonak	Bolero V70	Modulation-based	16
Oticon	Opn 1 PP	Synchrony detection	16
Resound	LiNX 3D 9	Spectral subtraction	17

The gain of the hearing aids was programmed according to the audiometric configuration set at 50 dB HL flat hearing loss with NAL-NL2 prescription formula via each hearing aid programming software. Two listening programs were set in each hearing aid: DNR on-maximum and DNR-off. The position of the listening program was counterbalanced for all hearing aids, where three hearing aids have DNR-on as Program 1 and another three have DNR-on as Program 2. The vent size was set to zero (no venting) and all additional features of the hearing aids, such as feedback cancellation and automatic or adaptive directionality, were switched off.

The test signals developed in Part 1 were saved as WAV files on a USB stick. By connecting the USB stick to the Audioscan Verifit system (Etymonic Design Incorporation, Ontario, Canada), the Speechmap application in the system will make those files available as stimulus selections. The sampling rate required for presenting the WAV files from USB is 32 kHz and 32 bit (Etymonic Design Incorporation, 2018). The test signal was presented to each of the six hearing aids at a 65 dB SPL input level through the loudspeaker of the test box. The output of each hearing aid with DNR on-maximum and DNR-off was recorded with the microphone on the 2 cc coupler. The HA output across octave and interoctave frequencies from 0.25 kHz to 6 kHz were documented in each test condition.

DATA ANALYSIS

In this study, efficacy is defined as the ability of DNR in hearing aids to result in attenuation in hearing aid output in response to noise signals. The difference output between DNR on-maximum and DNR-off was calculated at each frequency tested for all hearing aids. Originally, the RMS gain reduction calculation was separated by low frequencies (0.25-0.75 kHz), mid frequencies (1-2 kHz) and high frequencies (3-6 kHz). However, statistical analysis showed no significant difference in gain reduction at mid and high frequencies. Therefore, the data was combined between mid and high frequencies. The RMS gain reduction value for each hearing aid was calculated based on this formula:

RMS gain reduction $_{\text{low}}$ (dB) =

$$\sqrt[2]{\frac{GR^2{(0.25\,kHz)} + GR^2{(0.5\,kHz)} + GR^2{(0.75\,kHz)}}{3}}$$

RMS gain reduction $_{\text{mid-high}}$ (dB) =

$$\sqrt[2]{\frac{GR^2{(1\,kHz)} + GR^2{(1.5\,kHz)} + GR^2{(2\,kHz)} + GR^2{(3\,kHz)} + GR^2{(4\,kHz)} + GR^2{(6\,kHz)}}{6}}$$

These formulae were derived from Quar et al. (2019), which calculated the manufacturer's pre-fit output of hearing aid to compare with the Desired Sensation Level (DSL) child targets. The data were presented descriptively in the result section, followed by statistical analyses. The data were analysed using a three-way repeated measures ANOVA, with the RMS gain reduction as the dependent variable; the noise type (white and multi-talker babble noise), talker (female and male) and SNR levels (0, +5, and +10 dB) as the within-subject independent variables. Statistical analyses were performed with the IBM SPSS Statistics for Windows (version 25). The effect size of this study was $\eta^2 > 0.14$, hence the significance of the results was not compromised by the small sample size.

RESULTS

Figures 2 and 3 show the comparison of gain reduction observed from the output of each hearing aid between DNR on-maximum and DNR-off settings across frequencies tested (0.25 to 6 kHz) at different SNR levels with speech-plus-white noise signals and multi-talker babble noise of different talker.

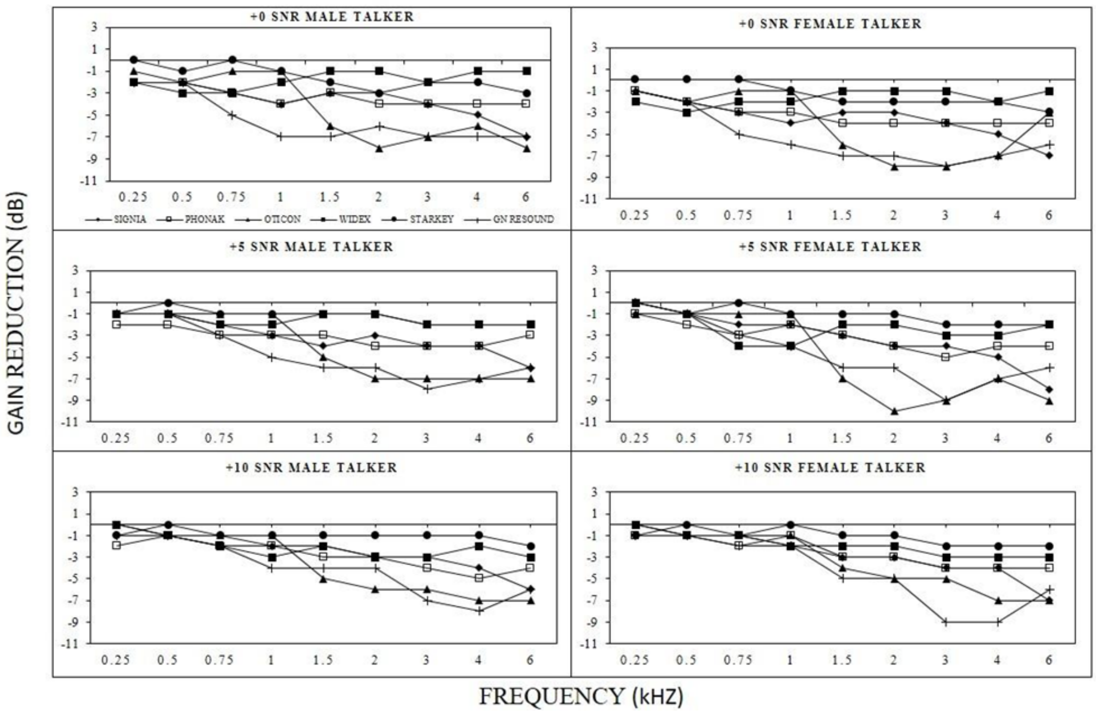

Figure 2 Comparison of gain difference observed from the output of each hearing aid across frequencies tested at different SNR levels with speech-plus-white noise signal of a different talker

Figure 2 shows that all hearing aids exhibit gain reduction across frequencies in the white noise conditions. The gain reduction was less than 5 dB in the low frequency region, and the Starkey and Widex hearing aids showed a similar amount of gain reduction across frequencies as compared to other hearing aids tested. The Resound and Oticon hearing aids applied little gain reduction in the low frequency region but the highest amount of gain reduction (between 5 to 10 dB) relative to other hearing aids in the mid- to high-frequency region (1.5 – 6.0 kHz). The gain reduction applied by Signia and Phonak hearing aids was gradually increased across frequencies tested.

Figure 3 shows that in multi-talker babble noise conditions, most hearing aids exhibit gain reduction of not more than 5 dB in the low-frequency region but little or no gain reduction from mid to higher frequency region (0.75-6.0 kHz). The Resound hearing aid showed the highest gain reduction, with a consistent amount between 2 to 8 dB across frequencies.

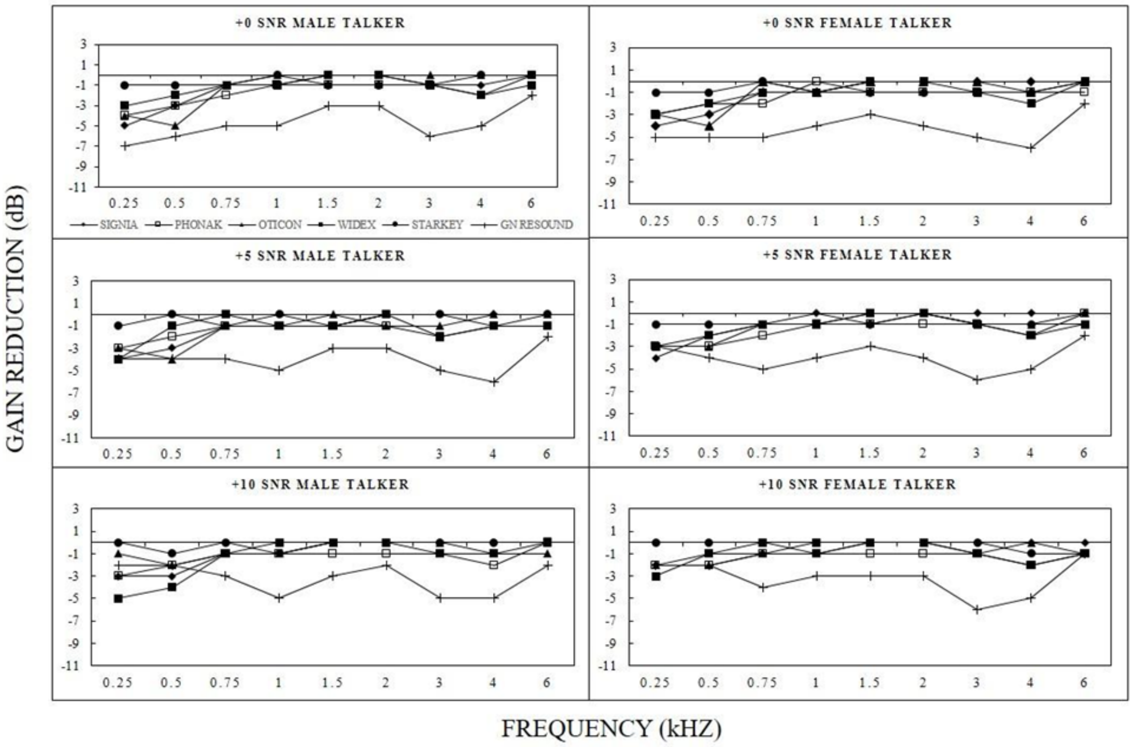

Figure 3. Comparison of gain difference observed from the output of each hearing aid across frequencies tested at different SNR levels with speech-plus-multi-talker babble noise signal of different talkers

The RMS gain reduction values for DNR of six hearing aids for low-frequency and high-frequency regions are given in Table 2 and 3, respectively. All RMS gain difference values for the low-frequency region were normally distributed. Mauchly's test showed that the SNR factor violated the sphericity assumption, hence the Huynh-feldt correction was used to interpret the data. There were significant main effects of noise [($F(1, 5) = 9.46$, $p = 0.03$, $\eta^2 = 0.65$; SNR, $F(1.089, 5.443) = 8.84$, $p = 0.03$, $\eta^2 = 0.64$)] and talker [($F(1, 5) = 14.32$, $p = 0.01$, $\eta^2 = 0.74$)]. There were significant two-way interaction effects between noise and talker [($F(1, 5) = 1.70$, $p = 0.25$, $\eta^2 = 0.25$)] and SNR and talker [($F(2, 10) = 2.87$, $p = 0.10$, $\eta^2 = 0.37$)] . However, there were no significant two-way interaction effects between noise and SNR [($F(2, 10) = 0.20$, $p = 0.82$, $\eta^2 = 0.04$)]. Post-hoc analysis using Bonferroni pairwise comparisons showed that RMS gain reduction under the multi-talker babble noise test condition was significantly higher than the white noise condition. The RMS gain reduction at 0 and +5 dB SNR test conditions was significantly higher than the +10 dB SNR condition. The RMS gain reduction obtained with male-talker speech signals was significantly higher than the female-talker speech signals.

Table 2. RMS gain reduction for low and mid-high frequency for six hearing aids obtain under speech-plus-white noise at three SNR levels

	Low-frequency RMS Gain reduction (dB)						Mid-high frequency RMS Gain reduction (dB)					
	Male talker			Female talker			Male talker			Female talker		
Hearing aids make and model	0	+5	+10	0	+5	+10	0	+5	+10	0	+5	+10
Signia Motion 2 px	2.38	0.82	0.58	1.25	0.82	0.58	4.55	4.12	3.61	4.55	4.73	4.14
Phonak Bolero V 70	1.37	1.37	1.00	1.25	1.25	0.82	3.85	3.54	3.63	3.85	3.79	3.34
Oticon Opn 1 PP	0.82	0.58	0.47	0.82	0.58	0.47	6.45	4.97	4.67	6.10	6.33	4.28
Widex Unique 440	1.56	0.82	0.75	1.37	1.37	0.47	1.15	1.41	2.21	1.15	2.26	2.08
Starkey Muse i1600	0.33	0.47	0.47	0.00	0.33	0.47	1.86	1.29	1.25	1.70	1.29	1.25
Resound LiNX 3D 9	1.91	1.11	0.82	1.83	1.05	0.82	5.59	5.23	4.68	5.61	5.31	5.29

Table 3. RMS gain reduction for low and mid-high frequency for six hearing aids obtained under speech-plus-multi-talker-babble noise at three SNR levels.

	Low-frequency RMS Gain reduction (dB)						Mid-high frequency RMS Gain reduction (dB)					
	Male talker			Female talker			Male talker			Female talker		
Hearing aids make and model	0	+5	+10	0	+5	+10	0	+5	+10	0	+5	+10
Signia Motion 2 px	1.97	1.70	1.45	1.70	1.53	0.82	0.71	0.58	0.41	0.41	0.41	0.41
Phonak Bolero V 70	1.80	1.25	1.25	1.37	1.56	1.00	1.15	1.22	1.15	0.91	1.15	1.22
Oticon Opn 1 PP	2.16	1.70	0.82	1.67	1.45	1.00	0.00	0.58	0.58	0.47	0.58	0.47
Widex Unique 440	1.25	0.88	2.16	1.25	1.25	1.05	0.88	0.94	0.47	0.82	0.88	0.88
Starkey Muse i1600	0.58	0.47	0.33	0.47	0.58	0.00	0.58	0.47	0.33	0.75	0.75	0.58
Resound LiNX 3D 9	3.50	2.31	1.37	2.89	2.36	1.63	3.46	3.46	3.20	3.43	3.43	3.14

All RMS gain reductions for the mid-high frequency region were normally distributed. Mauchly's test showed that the interaction effect between noise and SNR violated the sphericity assumption, hence the Huynh-feldt correction was used to interpret the data. The result shows there were significant main effects of noise [($F(1, 5) = 713.92$, $p = 0.01$, $\eta^2 = 0.74$)], SNR [($F(2, 10) = 3.17$, $p = 0.09$, $\eta^2 = 0.39$)] and talker [($F(1, 5) = 9.48$, $p = 0.03$, $\eta^2 = 0.70$)]. There were significant two-way interaction effects of the noise and SNR [($F(1.125, 5.624) = 1.00$, $p = 0.40$, $\eta^2 = 0.17$)], noise type and talker [($F(1, 5) = 1.62$, $p = 0.26$, $\eta^2 = 0.24$)] and SNR and talker [($F(2, 10) = 3.00$, $p = 0.10$, $\eta^2 =0.37$)]. There was also significant three-way interaction effect between noise, SNR, and talker [($F(2, 10) = 2.54$, $p = 0.13$, $\eta^2 = 0.33$)]. Post-hoc analysis using Bonferroni pairwise comparisons showed that the RMS gain reduction under the white noise test condition was significantly higher than multi-talker babble noise condition and the RMS gain reduction obtained with female-talker speech signals was significantly higher than the male-talker speech signals. RMS gain reduction at +0 and +5 dB SNR test conditions was significantly higher than the +10 dB SNR condition and the RMS gain reduction obtained with female-talker speech signals was significantly higher than the male-talker speech signals.

DISCUSSION

This study aimed to develop speech-plus-noise test signals that incorporate Malay sentences for quantifying the efficacy (i.e, amount of attenuation) of the DNR systems in commercial hearing aids. Generally, the test signals in the hearing-aid analyser for examining the efficacy of DNR are noise signals only. Scollie et al. (2016) suggested using speech-plus-noise signals in testing the efficacy of a DNR system because this type of signal will produce a more realistic representation of the amount of attenuation produced by the DNR system. Hence, this study developed speech-plus-noise test signals that can be used to test the efficacy of DNR in the hearing-aid analyser and at the same time, the test signals can also be used to test speech perception among Malay-speaking users in the future. In the current study, we carefully selected the speech materials and decided to use the MyHINT Malay sentences (Quar et al. 2008) that have been validated among Malay adult speakers. This is because in our future studies, testing Malay-speaking listeners using test materials in other languages may affect the performance of the participants. For example, Hochmuth et al. (2015) found that language and talker-specific had effects on speech intelligibility in noise and reverberation using the recording of bilingual talkers. The study showed the language-specific effect was found for German-Spanish bilingual talkers. Talkers speaking in Spanish showed a higher Speech Reception threshold (SRT) than those of the same talkers speaking in German. In fact, apart from using Malay language test signals, other factors need to be considered for assessing speech intelligibility in noise such as SNRs and types of noise. During the development of our test stimuli, we carefully controlled the SNR voltage between the Malay sentences and noise to achieve the desired SNRs. The RMS voltage for the digital sound files of the Malay sentences was kept constant while the RMS voltage for the noise sound files was varied to achieve the desired SNRs (0 dB, +5 dB, +10dB SNR). We also developed the multi-talker babble noise using recorded Malay passages. Multi-talker babble noise was selected as the competing background noise because it is the most common environmental noise encountered by listeners in everyday life. Our study showed that it is feasible to use the newly developed Malay sentence-plus-noise signals to test DNR.

This study also found that each hearing aid achieved a different amount of gain reduction at different test conditions, which is consistent with previous studies that found large differences in how DNR works in commercial hearing aids (Brons et al 2013b, 2014; Hoetink et al., 2009; Smeds et al 2009; Sørensen & Jespersen, 2015). Generally, the amount gain reduction can be as much as 10 dB in a given frequency region. Hoetink et al. (2009) compared gain reduction of DNR in 12 models of hearing aids and found that all hearing aids showed different gain reductions across frequency channels in which the maximum gain reduction by the hearing aids ranged from 0 to 15 dB. The hearing aids were tested in several fixed conditions differing in levels of the input signals (65 and 80 dB SPL), SNRs of the input signals (-9, -6, -3, 0, +3, +6, +9 dB) and the audiometric configuration (40 & 60 dB flat loss). The study used the International Collegium for Rehabilitative Audiology (ICRA) track-5 (single male talker) as the speech signal and ICRA track 1 (single talker without modulation) as the noise signal. In contrast, this current study presented the speech-plus-noise signals at 65 dB SPL and different SNRs (0, +5 and +10 dB), and audiometric configuration of 50 dB HL flat loss. We used Malay sentences recorded from a single male or female talker as the speech signals, white noise and multi-talker babble noise. Despite these differences, our study showed that the amount of gain reduction produced by the DNR systems (0-9 dB) were comparable with the amount of reduction reported in the literature.

The current study showed that in the speech-plus-white noise condition, all hearing aids had reduced output in all frequency bands. For the speech-plus-multi talker babble noise condition, two hearing aids reduced the gain in all frequency bands while three other hearing aids reduced the gain in the LF-band only. Only one hearing aid reduced gain in the LF-band and HF-band and not MF-band. This is consistent with previous study where Hoetink et al. (2009) found that all hearing aids showed different gain reductions at different frequency channels. For example, they reported that three of the hearing aids reduced the gain in all frequency bands while three other hearing aids reduced the gain in the low-frequency band (LF- band) and high-frequency band (HF-band) but not in the mid-frequency band (MF-band). Two hearing aids reduced gain in the LF-band and MF-band, and one hearing aid reduced gain in the LF-band only. One hearing aid surprisingly reduced gain in the MF-band and HF-band and not in the LF-band. Meanwhile, two hearing aids gave no reduction at all. However, white noise caused more gain reduction in hearing aids than multi-talker babbles, particularly in the mid-high frequency regions (as shown in Figure 1 & 2).

Prior to statistical analysis, RMS gain reductions were calculated separately for low frequency and mid-high frequency regions due to varied amounts of gain reduction in these regions as shown in Figure 1 to 2. In the mid to high-frequency region, there was higher gain reduction shown by the majority of the hearing aids when examined in the white noise condition as compared to the multi-talker babble noise condition. For example, the GN Resound, Oticon and Signia hearing aids showed extra gain reduction in the mid to high frequency region for the speech-plus-white noise condition. Conversely, there was a small amount of gain reduction applied at the low-frequency region and little or no gain reduction at the mid and high-frequency regions except GN Resound hearing aid for multi-talker babble noise condition. This result was consistent with previous studies where the study compared gain reduction using different test signals (Bentler & Chiou 2006; Bentler et al. 2008; Ng et al 2013). The study showed higher gain reduction applied for random noise (e.g., white noise) test signal while little or no gain reduction for speechlike noise (e.g., speech in babble noise). This pattern is comparable with a previous study where Hoetink et al. (2009) reported three typical gain reduction patterns: i) broadband reduction, ii) low- and mid-frequency band reduction, and iii) strong low- and high-frequency band reduction. Specifically, there were two patterns of gain reduction in the white noise condition: broadband gain reduction and stronger gain reduction at mid to high-frequency regions whereas gain reduction at low and high-frequency regions were observed in the multi-talker babble noise condition (Hoetink et al. 2009).

White noise is a steady-state noise with fewer envelope modulations than the multi-talker babble noise. In addition, white noise has a flat spectrum across frequencies (equal power for all frequencies) but multi-talker-babble noise has a sloping spectrum (i.e., more power at low frequencies and less power at higher frequencies). Generally, speech spectrum also has a sloping spectrum as the pink noise. Because the majority of the hearing aids examined in the current study have modulation based DNR algorithms, white noise is expected to result in more gain reduction at mid-to high frequency regions as the power of white noise at these regions might be more than the power of speech signals. Because multi-talker babble noise has more a speech-like spectra, some DNR algorithms may provide less or no gain reduction at high frequency band in order to preserve speech audibility and increase listening comfort perceived by the hearing aids wearer. In fact, several manufacturers have decision rules implemented to limit the maximum noise reduction allowed across channels in the presence of noise in all channels.

There was a significant main effect of SNR on RMS gain reduction suggesting that varying the signal-to-noise ratio of the input has an effect on gain reduction. Gain reductions at the low-frequency and mid-high frequency region were higher at +0 and +5 dB SNR in most hearing aids as compared to the +10 dB SNR level. This result was expected because the amount of gain reduction will be less in better SNR conditions (higher SNR). However, more gain reduction will occur in poorer SNR conditions (the lowest SNR 0 dB). This finding was consistent with previous studies (Bentler & Chiou 2006; Hoetink et al. 2009; Smeds et al. 2009). The study showed a higher amount of gain reduction applied at lower SNR by most of the hearing aids tested. However, this study found that the RMS gain reduction for mid-high frequency showed no significant main effect of SNR.

According to Bentler and Chiou (2006), the activation of DNR systems and the amount of gain reduction may be based on the estimated input level by the DNR systems in most hearing aids. The study also found that by varying the SNR of the input, it has the effect on reducing low-frequency gain. However, some algorithms showed less impact in the low-frequency region, with a slight increase in the gain for the mid and higher frequencies. They also stated that each manufacturer would consider the impact of determining the ratio of SNR that activates the DNR. The impact could be too much gain reduction that potentially limits the audibility of important information or too little gain reduction can potentially cause dissatisfaction with the hearing aid. Each manufacturer uses a different setting to set the threshold of activation for SNR.

This study found a significant main effect of the talker on gain reduction. Female-talker speech-plus-noise signals resulted in more gain reduction than the male-talker speech-plus signals at the higher frequency region but vice versa in the low-frequency region. This could be explained by the voice pitch difference between male and female talkers where male talkers have a lower voice pitch than females (Titze, 1989). These results may imply that using only one test signal may overestimate or underestimate the efficacy of DNR. Hence, it is recommended to use test signals with different modulations and different talker gender in order to be able to capture the differences in gain reduction exhibited by DNR in commercially available hearing aids.

In summary, it can be stated that DNR in most commercial hearing aids tested in this study showed differences in how they perform gain reduction when presented with different types of test signals and input SNR levels. DNR algorithm that used spectral subtraction in Resound HA showed higher gain reductions when tested with different test signals across frequencies, followed by HA Oticon, which used synchrony detection algorithm. Meanwhile, HAs with modulation based DNR algorithms such as Signia, Phonak, Starkey and Widex showed small amounts of gain reductions. Since the DNR system uses algorithms that analyse the modulation in the test signal, thus DNR is best tested with a speech-plus-noise signal since the speech signal also has modulation patterns. As digital signal processing chips improve and processing speed increases, more complex DNR algorithms may be applied. Therefore, the clinician should also verify hearing aids electroacoustically in a coupler or ear to ensure the intended effect is achieved on the patients.

This study used Malay sentence-in-noise test signals to evaluate the efficacy of digital noise reduction in commercial hearing aids. Most of the test signals available in a hearing-aid analyzer for testing the efficacy of DNR system in commercial hearing aids are using noise-only signals rather than speech-in-noise signals (Scollie et al., 2016). These two signals (noise-only vs. speech-plus-noise) generalise differently to real-world environments. This newly developed test signal can be used for electroacoustic testing so that clinicians can demonstrate clear differences between DNR strength measured with noise only versus measures made with speech mixed with noise. In addition, the newly developed test signals can also be used for speech intelligibility tests in future studies for Malaysian hearing aid users who speak Malay language. These newly developed test signals can help clinicians compare commercial products and choose the most suitable hearing aids when dispensing to clients based on their listening needs (i.e., stronger vs. milder DNR system) and possibly to help fine-tune the hearing aid. For example, if a patient's main concern is listening comfort in noise, perhaps the clinician can choose a hearing aid with stronger gain reduction such as Resound, Oticon, Signia and Phonak for hearing aid trials. Based on the electroacoustic testing results, the clinicians can adjust the strength of the DNR setting during the fine-tuning session. Otherwise, the patient can try Widex or Starkey hearing aids for other options. However, further evaluations (e.g., outcome measures) need to be done because hearing aids satisfaction depends on individual perception and other factors such as patient's expectations, financial issues, or listening conditions. Furthermore, the current study did not measure the effectiveness of the DNR system on patients. Speech intelligibility assessment and self-report measures could also provide useful information across a variety of domains that can be useful in the management process.

CONCLUSION

This study examined the efficacy of DNR in commercially available hearing aids by using Malay sentence-plus-noise test stimuli developed in-house. The results showed that types of noise, SNR levels, and talker gender significantly affected the amount of gain reduction exhibited by DNR across hearing aids tested. The results showed that it is feasible to use the newly developed stimuli to test the efficacy of DNR in hearing aids. Therefore, the clinicians need to measure the quality of the hearing aid by using a hearing aid analyser and other methods to verify the hearing aid's functionality prior to the fit. It is also critical to understand how inputs to the hearing aids during the fitting process would impact real-world success.

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CONFLICTS OF INTEREST

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

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