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Subjective Differences between Premium and Mid-level Digital Hearing Aids

Dakota Sharp

A dissertation submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment of the Requirements

for the degree of

Doctor of Audiology

Department of Communication Sciences & Disorders

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FACULTY COMMITTEE:

Committee Chair: Ayasakanta Rout, Ph.D.

Melissa Garber, Au.D.

Yingjiu Nie, Ph.D.

Dedication

This project is dedicated to my beautiful, brilliant wife, whose support and love carried me through this process.

Acknowledgments

I would like to thank my advisor, Dr. Ayasakanta Rout, and exceptional committee members, Dr. Melissa Garber and Dr. Yingjiu Nie, for their support and guidance throughout this project. Thank you also to Megan Hunter for her assistance and dedication to this project, and Dr. Chelsea Howard for the foundation she laid for this research.

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Abstract:

This study compared perceptual differences between premium and mid-level hearing aids from a major manufacturer in normal hearing listeners. Limited literature currently exists comparing perceptual differences between premium and mid-level digital hearing aids. This information is highly important in decision-making for clinicians and patients alike. Barry et al. (2018) evaluated four major hearing aid models' noise reduction properties and determined that one manufacturer's premium and mid-level devices demonstrated significant differences in noise reduction gain in frequencies associated with human speech. We programmed this device for a mild sloping to moderately-severe SNHL using the manufacturer's proprietary fitting formula and noise reduction at its maximum setting.

The hearing aid was mounted on KEMAR and ten Hearing in Noise Test (HINT) sentences were recorded with each device (premium and mid-level) at two different signal to noise ratios (SNR): 0 dB SNR and +5 dB SNR. Normal hearing listeners ($n = 19$) were blindly presented with the pair of stimuli at each signal to noise ratio condition with a three-alternative forced choice paradigm, whereby they indicate which presentation they preferred, or if there was no perceptual differences between the recordings. The preferences were made by each subject on the basis of three different criteria: noisiness, speech intelligibility, and overall quality.

The findings of this study are consistent with previous research and suggest that there is no subjective difference between premium and mid-level hearing aids on measures of noisiness, speech intelligibility, and overall sound quality. Overall, data suggested that participants did not perceive a statistically significant difference between

technology levels for either the 0 dB SNR condition or the +5 dB SNR condition. This suggests that in both very noisy and less noisy environments, normal-hearing listeners do not perceive any advantage when listening with premium technology. Future research should examine premium and mid-level technology with objective outcome measures and utilize subjects with hearing loss. It may be useful to examine differences between the devices on measures of listening effort as well.

Introduction and Literature Review:

Of the features of modern digital hearing aids most touted for their role in improving patient experience, none have been quite as discussed as noise reduction. However, audiologists and hearing aid dispensers rarely discuss or understand how the technology works, or what exactly occurs on a signal processing chip when noise reduction takes place. As hearing aids transitioned from analog processing to modern digital processing paradigms in the late 1990s, a signature complaint of users was the lack of clarity of speech when background noise is present (Alcantara et al., 2003; Bentler, 2005). Early digital hearing aids without noise reduction features utilized an omnidirectional microphone, which was beneficial for enhancing speech stimuli in quiet environments. However, with the introduction of noise in the communication environment, the devices were not capable of distinguishing the signal in any way-- which often led to amplified noise along with amplified speech (Alcantara et al., 2003; Bentler, 2005). Repeated market surveys have additionally promoted speech in noise as a common frustration for hearing aid users (Abrams & Kihm, 2015). These problems guided hearing aid manufacturers into investing research and development into processing strategies that would enhance the signal to noise ratio (SNR) and hopefully improve listening in noise outcomes.

The first step in developing these noise processing strategies requires a specific designation for inputs that would be described as “noise.” Problematically, there is no clear differentiator for what defines a signal as noise versus a desired input. For each individual user, the determination of what constitutes as noise can be dependent on a variety of factors, including environment, affect, and circumstance (Bentler & Chiou,

2006). This means that in some instances inputs such as music, environmental sounds, and even speech can be classified as noise by a hearing aid user, but in other times would be classified as the desired signal (Bentler & Chiou, 2006). These limitations led manufacturers to make generalizations about noise preferences in order to best serve the hearing aid user population at large. Modern noise reduction algorithms are therefore deemed effective on the basis of listening comfort and speech intelligibility or clarity (Bentler, 2005; Bentler & Chiou, 2006; Brons et al., 2013). Therefore, the major goal of any noise reduction algorithm is to improve the SNR of speech in noise without affecting the speech input (e.g. reducing the gain of speech or distorting the signal) (Bentler, 2005; Mueller et al., 2006).

Noise reduction algorithms have also sought to increase listener comfort in noisy situations (Bentler, 2005; Walden et al., 2000). As mentioned previously, early hearing aid strategies simply amplified sounds without consideration of the input type, including bothersome noise, which led to decreased listening comfort for hearing aid users (Bentler & Chiou, 2006). As noise reduction algorithms were developed, manufacturers were required to carefully balance decreasing noise input without reducing speech input. While reducing all inputs, including speech, would increase listening comfort in noisy environments, it would subsequently decrease speech intelligibility (Alcantara et al., 2003). Thus, listening comfort is an increasingly important and complex component of digital noise reduction.

Before discussing the outcomes of these noise reduction algorithms, it is important to establish an understanding of the signal processing techniques these algorithms utilize to accomplish the task. The first noise reduction algorithm utilized in

hearing aids was introduced in the 1970s (Bentler & Chiou, 2006). Analog hearing aids at that time used a tone switch to activate a low-frequency filter. As common, unwanted background noise (e.g. the hum of a fan or refrigerator, road noise, etc.) is typically comprised of low-frequency energy, the filter sought to decrease gain in the low frequencies to prevent the activation of the compressor and hopefully decrease the effects of the upward spread of masking (Bentler & Chiou, 2006). Other early noise reduction strategies including adaptive filtering or compression, or low frequency compression (instead of filtering), none of which led to improvements in speech-in-noise understanding (Bentler, 2005; Bentler & Chiou, 2006). Additionally, this low-frequency focus on noise reduction was unsuccessful due to its lack of consideration for sounds perceived as negative based on individual subject perceptual ratings that do not fall within low-frequency spectra (Warner & Bentler, 2002).

Another shortcoming of analog noise reduction strategies was their confinement to a single channel. With the advent of digital hearing aids, incoming signals could be processed in multiple channels simultaneously (Bentler, 2005). This advancement allowed for dedicated programs to make decisions regarding processing of specific inputs per frequency, intensity, and temporal characteristics, and then complete tasks such as gain reduction or filtering (Bentler & Chiou, 2006; Mueller et al., 2006).

A key spectral characteristic used in noise reduction strategies is modulation. Modulation refers to the features of a signal that change with time, typically described as modulation rate and modulation depth. When comparing speech and noise, speech typically has a deeper modulation depth and lower modulation rate, meaning fewer modulations (Bentler & Chiou, 2006). Noise reduction algorithms can then analyze

modulation rate in one or more frequency channels and determine whether noise is present and effectively reduce gain in that channel. Both modulation rate and depth are common features to help determine rules in modern digital noise reduction schemes (Bentler & Chiou, 2006).

While strides have been made in the ability of noise reduction algorithms to differentiate between speech and noise, the other important factor in noise reduction is just how much reduction should take place. Again, it is critical that with any attempt at noise reduction there is little to no reduction of the speech signal. Previous research has shown that there are clear differences between manufacturers regarding decision rules for gain reduction in noise reduction algorithms (Barry et al., 2018; Bentler & Chiou, 2006; Brons et al., 2013). A minimum input level for activation ideally results in no decrease in speech frequency gain in situations where there is no bothersome background noise. However, each manufacturer utilizes a proprietary algorithm for decisions when it comes to noise reduction activation and level.

After considering the years of research and development of noise reduction algorithms in digital hearing aids, it would make sense that their performance results in decreased difficulty understanding speech in the presence of background noise for hearing aid users. However, objective studies have reported mixed outcomes. A research paradigm for assessing benefits of digital noise reduction was developed by Walden et al. in 2000. In this model, hearing aid user performance was assessed as a comparison of the hearing aid in omnidirectional, dual-microphone directional, and a combination of dual-microphone directional with digital noise reduction activated (Walden et al., 2000). Participants were evaluated objectively using the Connected Speech Test (CST) and the

Profile of Hearing Aid Benefit (PHAB). Subjectively, participants completed ratings of speech understanding, listening comfort, and sound quality/naturalness using 11-point scales (Walden et al., 2000). Results indicated that significant improvements were gained from the dual microphones compared to the omnidirectional microphones, but that did not generalize to daily listening environments (Walden et al., 2000). The only significant difference reported from the use of noise reduction was improved listening comfort, but no significant improvement in speech understanding or sound quality was reported (Walden et al., 2000).

The use of comparison of hearing aid user benefit with microphone directionality to digital noise reduction did not stop here. Boymans and Dreschler (2000) did not find a significant difference in hearing aid users' performance on a speech recognition in noise task in a noise reduction on and noise reduction off setting. However, there were clear benefits from using a twin microphone system, and subjective ratings determined noise reduction ON decreased averseness to sound (Boymans & Dreschler, 2000). Another study did not find any significant increase in user satisfaction or speech intelligibility while noise reduction was active (Alcantara et al., 2003). However, they argue that there was no decrease in performance or satisfaction when the noise reduction was active either (Alcantara et al., 2003).

Ricketts and Hornsby (2005) focused on digital noise reduction effects on sound quality in a speech-in-noise environment. The study utilized two different speech-in-noise conditions (+6 dB SNR and +1 dB SNR) and also compared omnidirectional and adaptive directional microphone modes (Ricketts & Hornsby, 2005). Fourteen subjects were fit with bilateral digital hearing aids and assessed for speech recognition with the

Connected Speech Test (CST) and sound quality using paired comparisons of listening to the CST stimuli (Ricketts & Hornsby, 2005). For the objective measure of speech recognition, scores were not impacted positively or negatively by the presence of noise reduction, but results were in agreement with previous research that points to clear improvements for speech-in-noise using directional microphones rather than omnidirectional microphones (Ricketts & Hornsby, 2005). For the subjective preference, however, noise reduction ON was selected significantly more than noise reduction OFF (Ricketts and Hornsby, 2005).

Perhaps the most extensive early systematic review on hearing aid user benefit with digital noise reduction came from Bentler in 2005. The study was completed due to the increase in hearing aid manufacturers purporting the benefits of their proprietary digital noise reduction without providing published research verifying the claims (Bentler, 2005). Nine studies met inclusion criteria and were considered to support the effectiveness of directional microphones. Two studies met inclusion criteria for their analysis of noise reduction benefits, and evidence for benefit was unclear. Multiple subjects across studies did report a preference for the noise reduction on compared to off, even in tasks where a significant difference in benefit could not be determined. It should be noted that all studies included had a small sample size and poor power, which essentially rendered their results somewhat incapable of determining worthwhile differences (Bentler, 2005).

Another systematic review of digital noise reduction effects on speech intelligibility, sound quality, and listening effort was completed by Magudilu et al. in 2018. They compiled studies from six databases, only using research published after

2006, and obtained thirteen articles that met inclusion criteria with a wide variety of effect sizes (Magudilu et al., 2018). Their analysis indicated no improvements in speech intelligibility with noise reduction ON across included publications; however, subjective perceptual measures such as sound quality judgment resulted in moderate to large positive effects when digital noise reduction was ON (Magudilu et al., 2018). Results from this more recent meta-analysis were consistent with Bentler (2005) results: noise reduction does not improve objective outcome measures like speech intelligibility, but does improve perceptual outcome measures like sound quality ratings.

The question remains: if noise reduction is not offering a measurable improvement in speech intelligibility in noise, why do some hearing aid users continue to perceive a benefit and prefer noise reduction ON compared to OFF (Bentler, 2005; Boymans and Dreschler, 2000; Magudilu et al., 2018; Ricketts and Hornsby, 2005)? Continued research attempts to discern a measurable benefit or perceptual difference using digital noise reduction algorithms in modern hearing aids. In 2013, Brons et al. compared scores of perception using different hearing aid manufacturer noise-reduction systems to determine if a perceptual difference existed, and if so what factors contribute to hearing aid user preference. They first developed an inverse filter for each manufacturer's signal processing in order to remove perceptual and frequency response differences from a hearing aid's recording while signal processing is turned off, which creates a recording where all hearing aids utilized are perceptually equal to a listener. Then, when noise reduction is turned on, the only differentiating factor between manufacturers is the perceivable difference in noise reduction (Brons et al., 2013). This first part of the study revealed that noise-reduction implementations differed between

hearing aid manufacturers. Of note, all hearing aids utilized required the use of linear gain in order to remove non-linearity as a possible perceptible factor, and each had the maximum option for noise reduction active (Brons et al., 2013).

A sample of 10 normal-hearing subjects performed a paired-comparison rating, an intelligibility task, and a listening-effort rating (Brons et al., 2013). For the paired-comparison rating, subjects gave a preference between the noise reduction ON and OFF conditions for two different dB SNR conditions based on noise annoyance, speech naturalness, and overall preference, with the option of no difference between samples. Intelligibility was measured as a percentage of correct word responses at each dB SNR condition with the noise reduction ON and OFF. Finally, listening-effort was rated on a 9-point scale from “no effort” to “extremely high effort,” for five processing conditions at three different dB SNRs. Noise reduction was able to reduce annoyance of babble noise in both dB SNR conditions and with each manufacturer. In support of previous studies, listeners preferred noise reduction ON to noise reduction OFF, but noise reduction provided no measurable benefit for intelligibility or listening effort (Brons et al., 2013).

In 2014, Brons et al. continued their research with twenty subjects that have moderate sensorineural hearing loss to determine the perceptual effects of noise reduction in three different hearing aids. They hypothesized that the reduced frequency sensitivity and modulation detection of hearing-impaired listeners may affect sensitivity to processing differences, but that their increased difficulty understanding speech-in-noise may increase their performance with noise reduction algorithms activated (Brons et al., 2014). Speech intelligibility was measured using an SRT-50 and then fixed SNR level of +4 dB SNR; listening effort was rated on 9-point scale; and subjective perceptions of

noise annoyance, speech naturalness, and overall preference were rated with a paired-comparison task (Brons et al., 2014).

Results of this study were essentially in agreement with previous research that utilized normal-hearing subjects. Noise-reduction algorithms did not improve speech intelligibility, regardless of manufacturer or intelligibility task. However, also in agreement with previous results, noise reduction ON reduced perception of noise annoyance for participants. Interestingly, the noise reduction algorithm that had the most pronounced effect on noise annoyance and overall preference also resulted in the worst score for intelligibility. The authors suggest that this trade-off could be a useful tool both in establishing realistic expectations for hearing aid users, but also in using preference measures as a practical tool in conjunction with intelligibility measures to select noise reduction (Brons et al., 2014).

It is clear that noise reduction algorithms in modern digital hearing aids do provide benefit to hearing aid users. While that benefit may not be measurable using speech intelligibility tasks, it is a proven benefit perceptually for aiding with noisiness, clarity, and overall quality (Brons et al., 2014). Although further research is necessary to understand the relationship between these concepts, recent publications take these questions a step further. Specifically, hearing aid manufacturers often offer their devices at different price tiers, which typically coincide with different technology levels. Essentially a manufacturer will offer a hearing aid as a 'family', whereby 3-4 models exist at successively higher cost and sophisticated technology levels (Cox et al., 2014).

While hearing aids at the basic level may include common features such as multichannel compression, directional microphones, and noise reduction, the premium

level devices are advertised as having more complex versions of these features, and sometimes include features that the basic devices lack entirely (Cox et al., 2014). Hearing aid manufacturers claim that with an increase in technology level (and therefore, cost), there would also be an increase in the benefit that the user experiences; however, very little independent research has ever examined this claim (Cox et al., 2014). This information is critical for clinicians and patients when making the important financial decision for which hearing aid technology level to purchase.

In 2014, Cox et al. conducted a comparison between premium and basic technology level hearing aids in adults with hearing loss. Their study included 25 adults with mild to moderate sensorineural hearing loss, all of which completed speech understanding tests, standardized questionnaires, and open-ended diaries. While speech understanding scores were significantly better in the aided condition compared to the unaided condition, there was no difference in performance when wearing the premium versus the basic level technology. The questionnaires-- which included the Abbreviated Profile of Hearing Aid Benefit (APHAB), Speech Spatial Qualities of Hearing Scale (SSQ), Device-Oriented Subjective Outcome (DOSO) Scale, and a rating of overall quality of life when listening with the devices-- had similar results. There was no significant difference in ratings for the premium compared to the basic technology, but participants did rate the aided condition as significantly better than the unaided condition. These results were similar across manufacturers as well, indicating no obvious preference regarding a specific brand of hearing aids. Overall, the higher cost of the premium technology was not associated with any discernible benefits for participants (Cox et al., 2014).

This research was continued by Cox, Johnson, and Xu in 2016 in a two-part study that focused on the daily life impacts of hearing aid technology with a larger sample size. A sample of 45 subjects with hearing loss wore four different sets of bilateral hearing aids for one month at a time. The design included a premium and basic technology level from two different major manufacturers. The first part of the study focused on highly subjective ratings from the participants (Cox et al., 2016). Each subject completed a hearing-related quality of life measure, a six-item rating questionnaire (e.g. speech clarity, noise bother, wearing the device, listening fatigue, sound comfort, and localization), and an interview that allowed investigators to capture the different priorities among subjects (Cox et al., 2016).

Their data analysis was mostly descriptive due to the perceptual outcome measures completed. Expectedly, both premium and basic hearing aids were effective in improving quality of life compared to no hearing aid use at all (Cox et al., 2016). However, the data did not indicate the premium devices produced more quality of life improvements than the basic devices (Cox et al., 2016). As for the rating questionnaires, all four hearing aids provided substantial effectiveness for the six criteria, but there was no difference in this effectiveness when comparing the premium to the basic level devices for solving problems (Cox et al., 2016). The final research question was simple: after experiencing the real world with this technology, did the participants prefer the premium devices over the basic devices? A comparison of overall preference revealed no significant differences between scores for the premium and basic technology (Cox et al., 2016).

The second part of this major study focused on objective outcome measures, specifically in the form of speech understanding using the Four Alternative Auditory Feature (FAAF) test in three different SNR conditions, standardized questionnaires (including the APHAB, SSQ, and DOSO test), and through participant diaries (Johnson et al., 2016). The speech understanding task not only examined performance as a score, but also measured listening effort alongside as participants indicated how effortful they found a group of trials to be (Johnson et al., 2016).

For the speech understanding task, listening with hearing aids resulted in significantly improved performance compared to listening without hearing aids for all three conditions, but there was no statistically significant difference between the premium and basic hearing aids (Johnson et al., 2016). For listening effort, unaided listening resulted in a higher reported amount of listening effort than aided for each condition except loud. Interestingly, a statistically significant difference was achieved between premium and basic technology when examining listening difficulty in the loud condition only (Johnson et al., 2016). However, this result was only for one of the hearing aid brands and was obtained with a small effect size (Johnson et al., 2016). This was the only finding that suggested a difference in performance between premium and basic level technology (Johnson et al., 2016). The standardized questionnaires and diaries did not offer a statistical difference when comparing results from the premium and basic hearing aids. Johnson et al. (2016) concluded that both premium and basic hearing aids are capable of providing essentially equal improvements to speech understanding and listening effort in daily life for actual hearing aid users, especially compared to no amplification at all.

While the findings from Cox, Johnson, and Xu offer insight into the performance differences-- or lack thereof-- between premium and basic technology, even less research has been conducted to examine the difference between premium and mid-level technology. In 2018, Barry et al. examined the objective processing differences between four hearing aid models at the premium and mid-level of technology. Their study investigated overall noise reduction using steady-state stimuli and then frequency-specific noise reduction. Their frequency-specific stimuli were created using notch-filtered ICRA noise, where the notch was filled with steady-state broadband noise that was frequency-shaped similar to ICRA noise. Three bandwidths of steady-state noise were then embedded at four frequencies to create twelve total frequency-specific stimuli. These stimuli would work to simulate a speech-in-noise scenario, whereby the noise exists in a specific pocket of the speech spectrum. Hearing aids mounted to KEMAR then had their output recorded in the presence of the steady-state and frequency-specific stimuli (Barry et al., 2018).

For steady-state noise reduction, no statistically significant difference was found between the premium and mid-level hearing aids in terms of total gain reduction and attack time (Barry et al., 2018). However, there was a significant difference between the technology levels' noise reduction capabilities when using the ICRA stimuli. Hearing aids from all manufacturers included in testing provided the highest amount of noise reduction for the notched noise at 500 Hz. This is in agreement with the common understanding of basic noise reduction in hearing aids (Bentler & Chiou, 2006). Only two manufacturer's devices reduced gain at the higher frequencies-- Starkey and Signia-- and for these devices only the premium technology completed the gain reduction.

Specifically, Signia's premium device provided 7-11 dB of gain reduction at 4000 Hz, while its mid-level device provided only 1 dB of gain reduction (Barry et al., 2018).

Although Barry et al. (2018) did reveal some processing differences between the premium and mid-level noise reduction algorithms, independent information regarding specific features from hearing aid companies is still limited. Most findings that can be obtained are limited to released publications from manufacturers themselves, often known as "white papers," which are typically not included in peer-reviewed academic journals. These resources are often the only articles clinicians and consumers have when making the expensive and important decision regarding hearing aid purchase. While oftentimes this research can be helpful in understanding the concepts and intent behind different technologies, it is rarely a completely trustworthy source due to the inherent bias of manufacturers using their data as a marketing tool. Governing bodies for audiologists such as the American Speech-Language-Hearing Association (ASHA) and American Academy of Audiology (AAA) require that clinicians utilize high-quality evidence to assist in decision-making for best possible patient care, a philosophy known as evidence-based practice (EBP). Using only the resources provided from manufacturers, it is challenging for clinicians to provide care that follows EBP.

Due to the findings from Barry et al. (2018), a follow-up study was proposed that further examines if the clear digital noise reduction differences between the premium and mid-level technology from Signia translate to perceptual differences for listeners. To date, there have been no studies that examine if there is a perceptual difference between the sound processing of a premium hearing aid compared to its mid-level technology counterpart. The results of the current study will contribute to the insufficiency of

independent research available to clinicians regarding measurable differences between premium and mid-level technology hearing aids. This will improve clinicians' ability to make recommendations, and thereby potentially improve expectations and outcomes for hearing aid users. The present study seeks to determine if there is a difference in the sound quality of premium versus mid-level hearing aid technology in terms of perceived intelligibility, noisiness, and overall sound quality.

Methods:

Study procedures were reviewed and approved by the James Madison University Institutional Review Board (Protocol #18-0340). Each participant gave written informed consent prior to the start of the study. Participants were not compensated for their time. All testing for this study was performed at the James Madison University Hearing Aid Research Laboratory.

Participants

Young, normal hearing listeners 18-30 years of age were recruited from the James Madison University student population to participate in this study. The participants were screened for hearing sensitivity at 20 dB HL between the octave frequencies of 500-4000 Hz according to the American Speech-Language Hearing Association (ASHA) recommended guidelines for hearing screening. Inclusion criteria in this study included a pass in the hearing screening and no self-report of upper respiratory problems at the time of the study that could potentially affect perception of sound quality. An a priori power analysis using G*Power 3 software (Faul, Erdfelder, Lang & Buchner, 2007) indicated a required sample size of 12 subjects to achieve a power of 80% with a medium effect size at an alpha level of 0.05. A total of 20 participants (17 females and 3 males, mean age 22.8 years) were included in the completed research. The larger proportion of female participants was a reflection of the student demographics within the Health and Behavioral Sciences areas at James Madison University.

Hearing Aids

A brand new receiver-in-canal style digital hearing aid was used as an exemplar device to process noisy speech sentences for the listening tests of sound quality. The hearing aid was manufactured by Signia and was marketed as S-Demo with a programmable option to change the hearing aid technology from entry-level basic to premium with all available signal processing features. For the current study the hearing aid was programmed at two separate levels of technology – mid-level and premium. The Signia S-Demo hearing aid was chosen for the current study based on the data of Barry et al. (2018) which showed a greater degree of noise reduction for the premium level of technology compared to the mid-level technology. Additionally, since this hearing aid model comes with a flexible chip to program at a certain level of technology, it was an ideal solution to control for other hearing aid related variables. The hearing aid was programmed with a mild sloping to moderate hearing loss, with all features implemented as recommended by the manufacturer. The manufacturer's proprietary fitting formula was applied to the two levels of technology.

Instrumentation and Recording of Speech Stimuli

All recordings were completed in an IAC double walled sound treated booth located in the Hearing Aid Research Laboratory. The programmed hearing aid was mounted on KEMAR's right ear which was placed at a 1 meter distance from a Tannoy System 6 speaker. The hearing aid receiver was coupled to the mannequin's ear and Knowles Electronic DB-100 2-cc coupler with a closed dome to obtain proper acoustical

seal. The output of the hearing aid was picked up by an Etymotic Research ½ inch condenser microphone connected to an ER-11 amplifier.

Ten sentences from the Hearing in Noise Test (HINT) (Nilsson, Soli, & Sullivan, 1994) were presented at 65 dB SPL through the Tannoy speaker located at 1 meter distance in front of the KEMAR mannequin. The sentences were presented at two different signal-to-noise ratios – 0 dB and +5 dB, making a total of twenty recorded sentences per hearing aid technology level (premium and mid-level). The processed HINT sentences were digitized and recorded on to the hard drive of a separate portable computer using commercially available audio editing software (Sony Sound Forge 9). A schematic diagram of the stimuli recording procedure is shown in Figure 1.

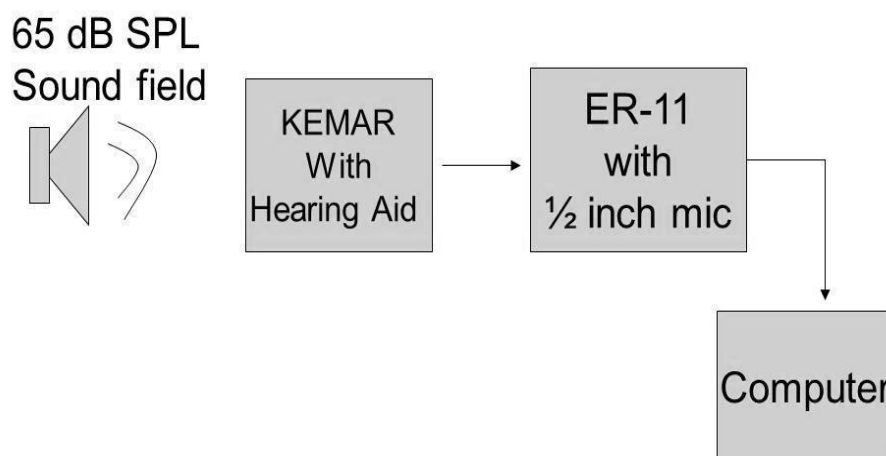


Figure 1. Schematic diagram of stimuli recording procedure.

Test Procedure

Participants were presented with 10 pairs of HINT sentences at each signal to noise ratio condition with a three-alternative forced choice paradigm. The paired comparison task was implemented in a commercially available software program (Superlab 4.5, Cedrus Corporation, San Pedro, CA). The stimuli were presented via a pair of Sennheiser HD 400 circumaural sound isolating headphones. After a paired presentation (premium v. mid), the participant pressed a button on the Cedrus RB-740 response pad to indicate his/her preference.

This method was based on a standard of the International Telecommunication Union (ITU-T P.835, ITU-T 2003), according to which subjects must give separate ratings for the speech signal, background noise, and overall quality. The ITU standard uses a rating scale to measure quality. Paired comparisons were used instead because they are more sensitive to small differences in conditions (Böckenholt, 2001). For the purpose of this study, speech intelligibility was defined as how well the listener perceived to understand the speech sentences regardless of the noise levels. Noisiness was defined as how noisy the sentences sounded. The listener was instructed to focus on the background noise only. Sound quality referred to the overall relative pleasantness of the quality of the sound. They were instructed to select the sentence from the pair which one they would rather listen to. The participants were provided with written instructions prior to the start of the study. Specific instructions for speech intelligibility are shown below. Instructions for the noisiness and overall quality tests were also presented in the same format.

“You will be presented a pair of sentences recorded in background noise. Please listen to the sentences carefully. Your task is to judge which sentence is MORE INTELLIGIBLE. Press the key labeled “1” on the response pad if you find the first sentence to be more intelligible (i.e. easier to understand). Press the key labeled “2” if the second sentence sounds more intelligible. If both sentences sound exactly the same, press the key labeled “no difference”. The differences are very subtle. Please listen carefully.”

Two versions of the paired comparison task were set up for each participant. In version A, stimuli processed through the premium technology was presented as the first sentence in the pair. Version B had the mid-level technology as the first sentence in the pair. The presentations of the two versions were counterbalanced across participants, and they were blinded to the test conditions. The participants were also given a practice trial to familiarize with the test set up. Each participant judged a total of 120 pairs of sentences resulting in 120 data points per person. The entire session lasted approximately 75 minutes per participant. A schematic diagram of all the test conditions is depicted in Figure 2.

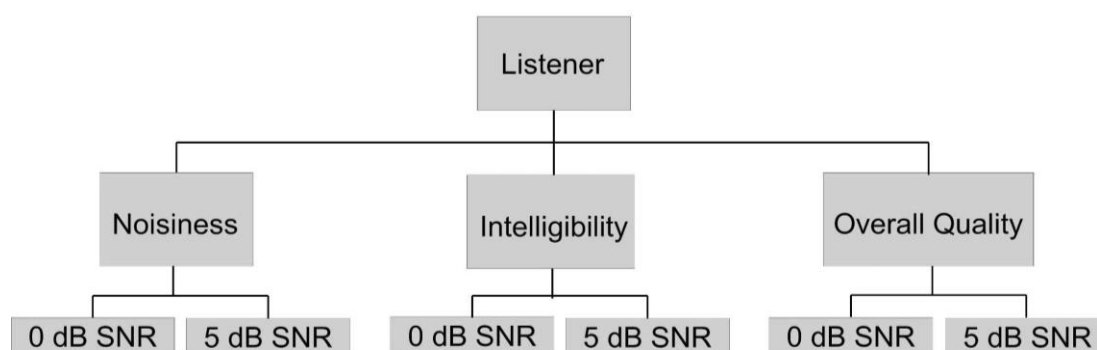


Figure 2. Schematic diagram of the testing procedure. Trials were counterbalanced to minimize order effect.

Data Analysis

All data for versions A and B were averaged and a Friedman non-parametric test was performed to evaluate the difference in preference for premium, mid-level, or no difference between the two technology levels. Separate Friedman tests were conducted for intelligibility, nosiness and overall quality. Post-hoc analyses were conducted with Wilcoxon signed-rank test to examine pairwise differences. In addition to the group statistics, individual data were examined via descriptive statistics to study individual variability.

Results:

The triad of preferences (premium, mid-level, or no difference between the two) were counted for each condition. Since the order of presentation of the premium and mid-level hearing aid processed sentences was counterbalanced, the results were combined prior to further data analysis. The results are presented in three sections: speech intelligibility, noisiness, and overall quality. Separate Friedman non-parametric tests were conducted to analyze the subjective preference for premium vs mid-level hearing aid. For all analyses p-value of <0.05 was set as the level for statistical significance. All the data points were examined for distribution and outliers prior to statistical analysis. After careful examination, the data collected from one participant were excluded from further analysis as this participant had pressed the “move to the next trial” key instead of the selection buttons for making preference judgments. As a result, a total of 19 subjects were included in the final analysis. In addition, it was noticed that one participant was presented with 110 out of the 120 pairs of sentences. The averaged data points were consistent with the rest of the participant’s data and it was included in further analysis.

Perceived Speech Intelligibility

Each participant’s preference judgement for premium, mid, or no difference was tallied for the 0 dB and +5 dB signal to noise ratio conditions. The frequency count was then converted into a proportion of the total number of stimuli the participants judged. Figure 3a shows the percent preference for the premium, mid, and no difference between the two technology levels. The data is presented separately for the two SNR conditions. Error bars indicate ± 1 standard error. This figure demonstrates that there was a slight

preference for the speech processed through the premium hearing aid compared to the mid-level technology. However, statistical analysis using Friedman non-parametric test did not yield any statistical significance between the three choices at 0 dB SNR ($\chi^2(2) = 1.861$, $p = 0.395$) and +5 dB SNR ($\chi^2(2) = 1.826$, $p = 0.401$). Post hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied which revealed no significant difference between the premium and mid-level at either signal to noise ratio levels ($p = 0.293$ for 0 dB SNR and $p = 0.334$ for +5 dB). It is also important to note that the participants chose the ‘no difference’ option in nearly one out of three trials. This indicates the minute difference in sound quality of the noisy speech processed by the premium and mid-level hearing aid technology.

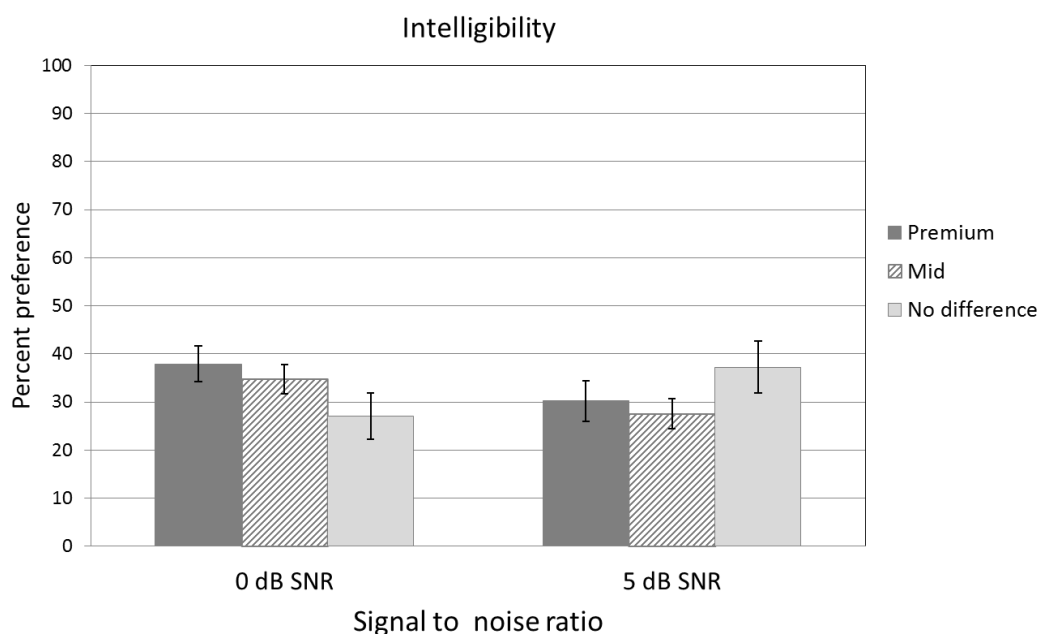


Figure 3a. Percent preference for the premium, mid, and no difference between the two technology levels in the **intelligibility** condition. The error bars indicate ± 1 SE.

There was large individual variability across participants' preference for the technology level. The individual data was sorted in a descending order of preference for

the premium level technology. A closer examination revealed that four participants (S4, S12, S17, and S20) consistently preferred the sound quality of the premium technology. Four listeners (S1, S2, S6, and S15) chose the ‘no difference’ option more than either of the hearing aid technology level. Only one participant (S 18) consistently preferred the mid-level technology for better speech intelligibility. The individual data are depicted in Figure 3b below.

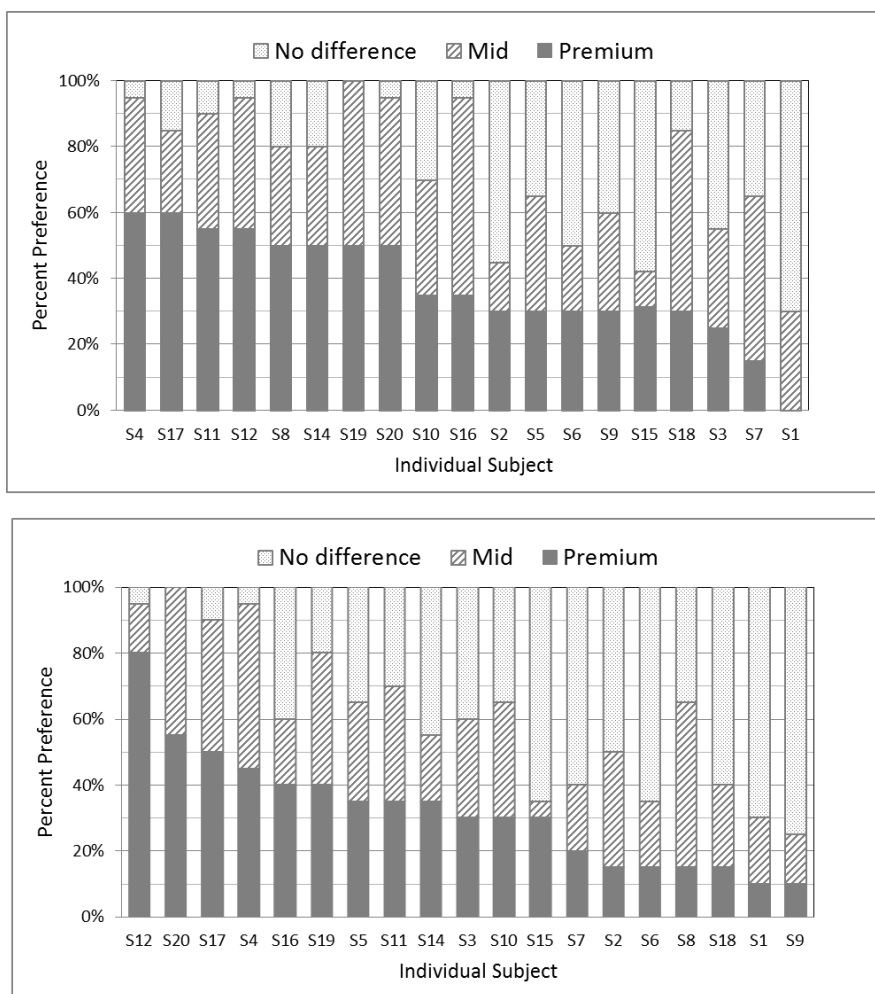


Figure 3b. Individual preference for the **perceived intelligibility** of premium vs. mid-level hearing aid technology. The top and bottom panels depict data for 0 dB and +5 dB SNR conditions, respectively. The participants are noted by their codenames (x-axis), and the data is sorted in terms of the preference for premium technology and color coded for the three choices (dark bars: premium, cross bars: mid-level, light: no difference).

Perceived Noisiness

The noisiness data were analyzed similar to the speech intelligibility data discussed in the previous section. Interestingly, there was a trend toward preference for mid-level hearing aid when the participants were judging for noisiness of the stimuli. Friedman non-parametric test, however did not result in a statistically significant difference ($\chi^2(2) = 4.274$, $p = 0.118$ for 0 dB and $\chi^2(2) = 2.054$, $p = 0.358$ for +5 dB SNR). Post hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied which did not yield any significant difference between the perceived noisiness between the premium and mid-level hearing aids ($Z = 1.441$, $p = 0.149$ for 0 dB SNR; $Z = 1.312$, $p = 0.189$ for +5 dB). The proportion of preference for premium, mid, or no difference is shown in figure 4a below.

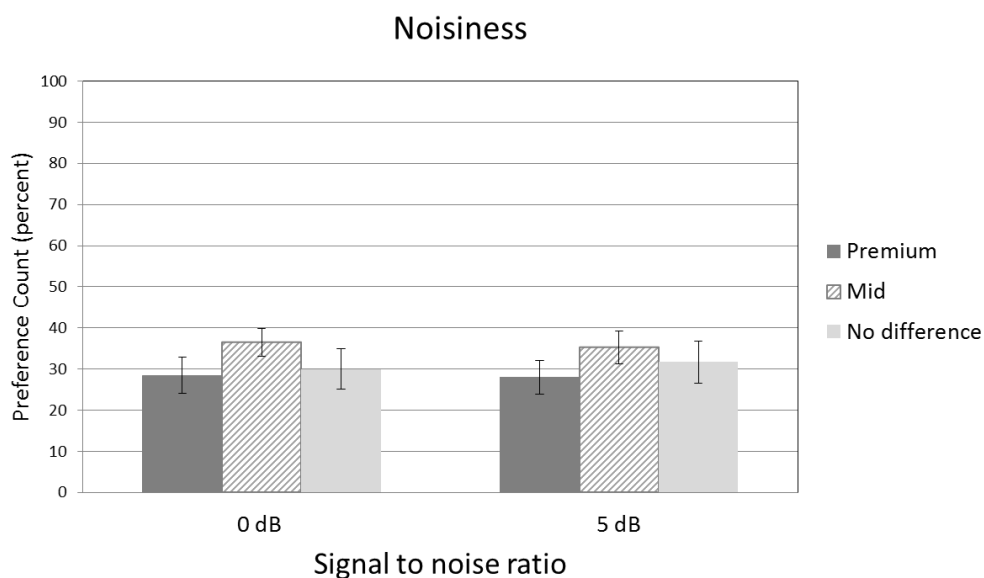


Figure 4a. Proportion of preference for the premium, mid, and no difference in the **noisiness** condition. The error bars indicate ± 1 SE.

The individual data for noisiness is depicted in figure 4b. There was large individual variability across participants' preference for the technology level. A closer

examination revealed that four participants (S6, S7, S8, and S15) chose the ‘no difference’ option more than either of the hearing aid technology level. Another four listeners (S11, S14, S17, and S18) chose the mid-level technology as being less noisy compared to the premium level. Only three subjects (S2, S4, and S12) rated the premium hearing aid as less noisy.

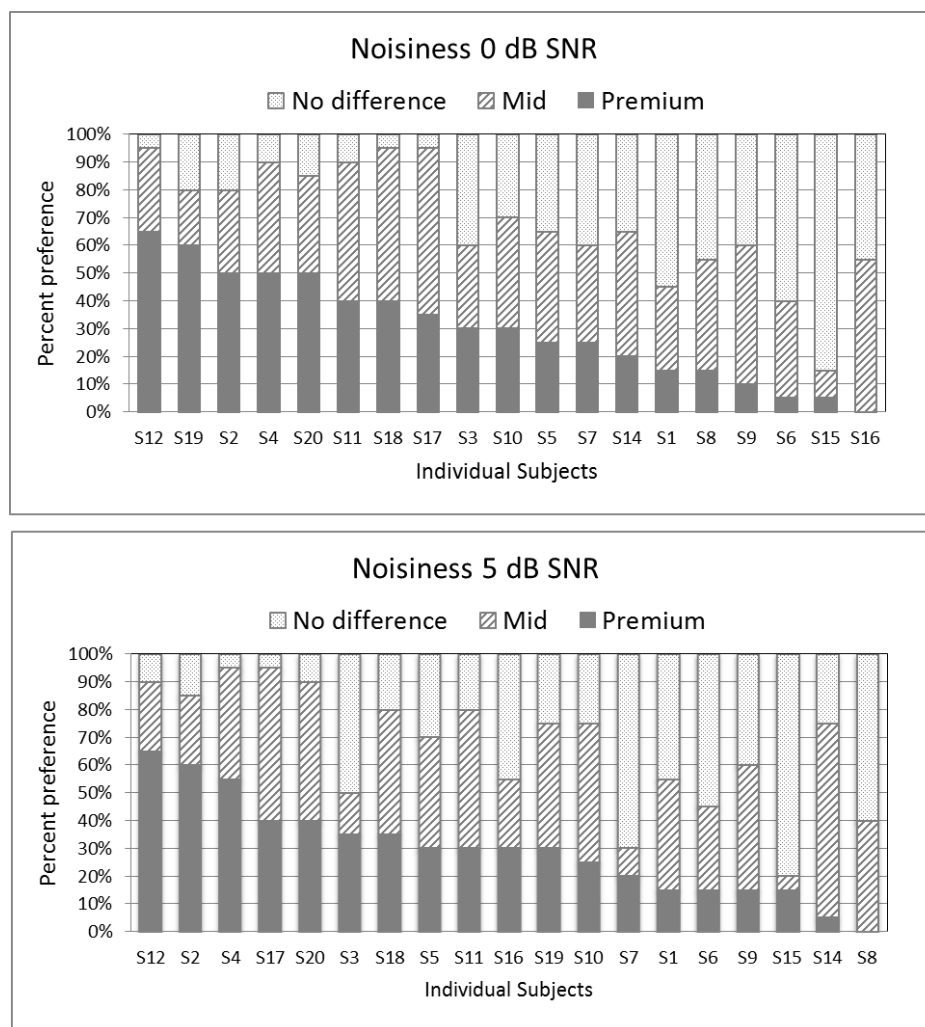


Figure 4b. Individual preference for the **noisiness** of premium vs. mid-level hearing aid technology. The top and bottom panels depict data for 0 dB and +5 dB SNR conditions, respectively. The participants are noted by their codenames (x-axis), and the data is sorted in terms of the preference for premium technology and color coded for the three choices (dark bars: premium, cross bars: mid-level, light: no difference).

Overall Sound Quality

Overall sound quality preference of premium vs. mid-level hearing aid technology resulted in similar findings compared with noisiness and intelligibility. For the 0 dB signal to noise ratio condition, the Friedman nonparametric test did not show any statistical significance between the three preference choices ($\chi^2(2) = 0.75$, $p = 0.687$). Similarly, at +5 dB SNR there was no significant difference ($\chi^2(2) = 4.081$, $p = 0.130$). Post hoc analysis using Wilcoxon signed-rank test confirmed that there was no significant difference between premium and mid-level technology at either signal to noise ratios ($Z=0.242$, $p=0.404$ and $Z= 1.508$, $p=0.065$, for 0 dB and +5 dB SNRs, respectively). The proportion of preference for premium and mid-level as well as no difference is shown in Figure 5a. Individual data is also shown in figure 5b. As it was the case with speech intelligibility and noisiness, there was a large variability cross the participants' responses.

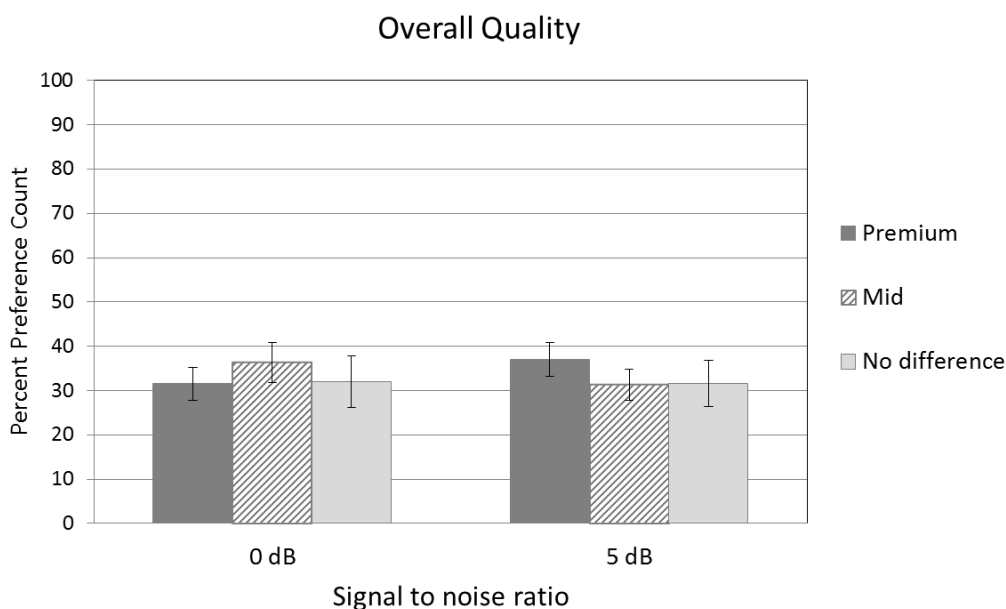


Figure 5a. Proportion of preference for the premium, mid, and no difference in the **overall sound quality** condition. The error bars indicate ± 1 SE.

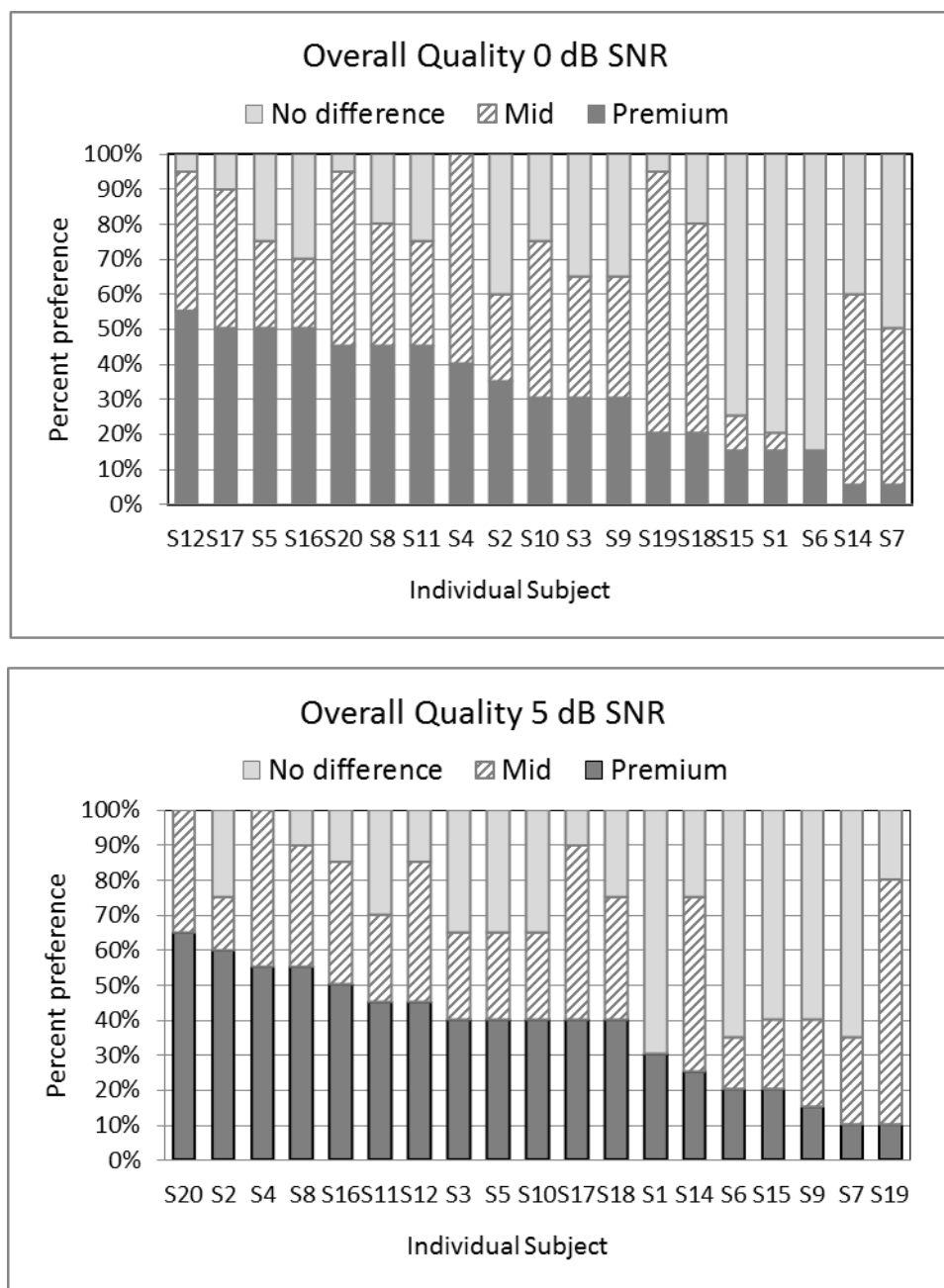


Figure 5b. Individual preference for the **overall sound quality** of premium vs. mid-level hearing aid technology. The top and bottom panels depict data for 0 dB and +5 dB SNR conditions, respectively. The participants are noted by their codenames (x-axis), and the data is sorted in terms of the preference for premium technology and color coded for the three choices (dark bars: premium, cross bars: mid-level, light bars: no difference).

Correlation between the Two Versions of the Listening Task

Pearson's correlation coefficient (r) was calculated in order to examine if there was an order effect of presentation. The participants were presented sentence pairs in such a way that in half of the trials a sentence processed with premium hearing aid was presented first while the other half of the trials had mid-level hearing aid as the first sentence in the pair. There was a strong positive correlation when the participants chose 'no difference' between the two hearing aid technology levels. However, there were weak to moderate correlation between the two versions of the test (premium presented first vs mid-level first). This result indicates that when the participants were choosing 'no difference' they were more likely to be consistent when the order of presentation was reversed. The low to moderate correlation further highlights the minute difference in the perceived sound quality of the two technology levels.

Discussion:

The findings of this study are consistent with previous research and suggest that there is no subjective difference between premium and mid-level hearing aids on measures of noisiness, speech intelligibility, and overall sound quality. Overall, data indicated that participants did not perceive a statistically significant difference between technology levels for either the 0 dB SNR condition or the +5 dB SNR condition. This demonstrates that in both very noisy and less noisy environments, normal-hearing listeners do not perceive any advantage when listening with premium technology. In the 0 dB SNR condition, subjects showed a slight preference for the premium technology when assessing which device offered better speech intelligibility, but this value did not achieve statistical significance. It is possible that the premium device may process speech in a way that slightly improves clarity in very noisy environments; but again, statistical significance was not reached.

In agreement with previous research, premium technology hearing aids offer no measurable benefit compared to their mid-level counterparts (Cox et al., 2014; Cox et al., 2016; Johnson et al., 2016). These results contribute to the conclusions that features often purported to make premium devices more advanced (e.g. increase number of compression channels, faster processing speeds) do not result in a perceptual benefit to listeners (Amlani et al., 2013). Although normal hearing listeners were used as the gold standard in the present study and discerned no difference, it is possible that hearing impaired users could be more sensitive to the difference as they have an increased difficulty in noise without amplification. Future research should explore this notion.

It is important to recognize the individual subject variability observed in this study and how that may impact clinical decision-making with hearing aids. Multiple subjects consistently preferred the premium technology, though their consistency was not enough to indicate the average subject perceived a difference. Future research should consider the valuable information of examining individual subject variability. Specifically, taking into consideration if performance consistently improves for a single subject when comparing technology levels. This may be particularly useful information for clinicians and patients alike.

The hearing instrument from Signia was chosen because of the significant difference in gain reduction between premium and mid-level hearing aids at frequencies mostly associated with speech (Barry, 2018). However, the stimuli used by Barry (2018) were a narrow band of steady state noise embedded in a wide band of fluctuating spectral content. It is plausible that the noise reduction algorithm at the two technology levels was not different in sensitivity to noise. While the premium hearing aid does a better job of reducing gain for steady-state noise, this difference may not generalize to more complex stimuli like what was used in the present study (HINT sentences in background noise). This result is consistent with previous research that examined steady-state noise reduction and complex noise reduction in hearing aids (Bentler, 2005; Bentler & Chiou, 2006).

It is possible that this method of noise reduction may lead to improved intelligibility in poorer SNR conditions, as seen in the slight preference for premium over mid-level technology for intelligibility in the 0 dB SNR condition. However, further research should explore these relationships between technology levels and speech intelligibility, with an emphasis on objective speech intelligibility measures such as

Hearing in Noise Test (HINT) or Speech in Noise (SIN) test scores. Hearing aid manufacturers have also begun reporting the benefits of reduced ‘listening effort’ while using their devices-- especially with premium technology. New research techniques are being developed to assess listening effort in human subjects, and future research should explore the listening effort differences between premium and mid-level technology.

The findings of this study are beneficial to clinicians and patients alike. Results provide empirical evidence from an independent source that no clear differences exist for preference between premium and mid-level hearing aids on a variety of subjective rating measures. Clinicians may use this data to inform their opinion regarding hearing aid manufacturer marketing techniques, and to help improve their decision making when providing amplification care to a person with hearing loss. While on one hand it is useful to know that overall data suggests no difference in preference, clinicians should also be mindful of the individual subject variability observed in the present study’s results. This observation may also assist clinicians in helping educate and counsel patients on how each person will have their own subjective experience with hearing aids, and it may be difficult to predict these differences.

This study did not include subjects with hearing loss, which may make it difficult to generalize to the hearing aid user population. However, previous studies using similar techniques also ran their initial experiment with normal hearing subjects and then completed follow-up research with subjects with hearing loss, and found the results were the same each time (Brons et al., 2013; Brons et al., 2014). Other studies using only subjects with hearing loss also found similar results (Cox et al., 2014; Cox et al., 2016; Johnson et al., 2016). The data obtained from the present study is salient and necessary as

very little literature exists regarding the relationship between premium and mid-level technology hearing aids, including their effects and outcomes on human subjects. Future research should consider utilizing objective measures like speech intelligibility as a comparison of premium and mid-level technology, especially in hearing aid models that demonstrate a difference in processing between the two levels (Barry et al., 2018).

It is also important to consider that these results represent a snapshot of a current hearing aid technology from a single manufacturer. The results of the present study should not be generalized to all manufacturers, and as hearing aids continue to advance and change rapidly new models with new features are introduced constantly. There are multiple features of the hearing aid working together to process inputs, not just noise reduction, and these features should also be considered when discussing the differences between devices (directional microphones, number of channels, etc.). However, clinicians and patients alike should remain aware of the lack of independent research that provides a demonstrable difference in performance between the hearing aid technology levels, and use this information to make the best possible decision regarding their amplification.

Limitations of the Present Study

The current study tested young, normal hearing listeners to examine the difference in the sound quality of two hearing aid technology levels. Normal hearing listeners were included because it was expected that if there were any subtle differences in sound quality, normal ears could detect those differences easily. However, it is well documented that there is tremendous variability among hearing impaired listeners, and this study

needs to be extended to evaluate if there is any difference between the two technology levels in this population. The paired comparison experiment was set up as an offline study. It would be more ecologically valid to compare the two technology levels in the real world. As discussed earlier, the results of this study may not be generalized to hearing aids from other manufacturers.

Conclusion:

This study sought to determine if a perceptual difference between premium and mid-level hearing aid technology existed for normal hearing listeners in order to improve clinician and patient awareness and decision-making, and assist in determining if the price difference between the two levels is associated with a distinction in sound quality. The study only evaluated one manufacturer's model, which represents a small snapshot of current hearing aid technology trends and features. It is impossible to determine if the results using only one device and generalize to all makes and models of hearing aid technology. However, with the limited amount of literature about this topic, a difference in preference or no difference in preference are both clinically important results.

The data of the present study reveals there is no difference in the sound quality of premium versus mid-level hearing aid technology in terms of perceived intelligibility, noisiness, and overall sound quality. Data collected for both the 0 dB SNR and +5 dB SNR conditions did not reveal any statistically significant preference for the premium over mid-level technology, either. The individual variability results did indicate that some subjects consistently preferred premium over mid-level technology, but this data did not indicate a group distinction that reached statistical significance. This information may indicate that some listeners are more perceptive of the differences in processing for premium compared to mid-level technology. However, this information is only useful as a general guideline that clinicians may use to establish and manage expectations in hearing aid users.

Using results only from this study would be insufficient to determine if there are no differences between premium and mid-level technology hearing aids. Further research

should explore objective outcomes, such as intelligibility tasks, and use additional models of hearing aids. Even though using normal hearing listeners can serve as a gold standard for small perceptual differences, it is also important that future research examine these differences using individuals with hearing loss. It is possible that their difficulty in these noisy listening situations will be measurable using a similar research paradigm.

Altogether, clinicians should always use evidence-based practice when determining patient care. For decades clinicians and individuals with hearing loss have had no choice but to use manufacturer marketing claims as their sole resource when making decisions regarding amplification. Research like the present study is critical to ensuring accountability from hearing aid manufacturers, and for promoting independent, evidence-based practice for clinicians. Further research is necessary for clinicians to make fully informed decisions regarding their patient care, but these authors implore clinicians to continuously seek independent literature for this information.

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