Objective differences between premium and mid-level digital hearing aids

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Objective Differences between Premium and Mid-level Digital Hearing Aids

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A dissertation submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

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Abstract:

This ongoing study compared premium and mid-level hearing aids from major manufacturers on noise reduction and general electroacoustic characteristics. The findings of this study will contribute to the scarce independent literature evaluating currently available hearing aid technology. Measuring the overall gain reduction in response to a steady state noise can objectively test noise reduction. However, such a method does not specifically test a hearing aid’s ability to reduce speech in specific narrow frequency bands. Hanline & Rout (2008) developed a set of stimuli to evaluate multichannel noise reduction algorithms more precisely. We used these stimuli to test noise reduction abilities of hearing aids. Premium and mid level digital hearing aids from four major manufacturers were obtained and programmed for mild to moderately severe sloping SNHL using the manufacturer’s proprietary fitting formula.

Each hearing aid was programmed for noise reduction ON and OFF with every other feature disabled (or minimized). Hearing aid programming was verified, and each hearing aid was tested twice for reliability. Three different bandwidths of steady-state noise (1/3 oct, 1 oct, 2 oct) were embedded at six different frequencies (0.5, 1, 2, and 4 kHz) resulting in 12 new stimuli. In addition, a 30 second steady state speech shaped noise was included to evaluate the attack time and overall gain reduction of each noise reduction algorithm.

The findings of this study suggest that there is no difference between the noise reduction efficiency of a premium level hearing aid when compared to a mid-level instrument at reducing steady state background noise. The frequency specific data indicated that there was a significant difference in the noise reduction capabilities of a
mid-level and premium level hearing instrument when the background noise included both speech and background noise, as simulated by the ICRA stimuli. ICRA stimuli was created by the International Collegium for Rehabilitative Audiology for the purpose of analyzing hearing aids, as it employs spectra shaped speech like noise (Dreschler et al., 2001). There was also a significant interaction between technology level and noise bandwidth as well as a significant main effect of noise bandwidth.
Introduction:

Noise reduction is a familiar term when discussing digital hearing aids today, however there is little evidence on its effectiveness. Noise reduction became a necessity due to the fact that the main complaint amongst hearing aid users who were fit in the early 2000s was that it was difficult to focus on speech in the presence of background noise (Alcantara et al., 2003). These users were typically fit with omnidirectional microphone patterns and without noise reduction features (Alcantara et al., 2003). Instruments that were fit in this manner were effective at enhancing speech in quiet environments, but when these hearing aids were used in the presence of background noise it actually resulted in amplification of the background noise as well. This led to no improvement of the signal-to-noise-ratio (SNR) and often led to reduced speech intelligibility. The reduced intelligibility was a product of the upward spread of masking, which was created as a result of the amplification of background noise. (Alcantara et al., 2003). It is a well known fact that in public places the SNR of conversation tends to be around +5 to +10 SNR, however research indicates that +10 to +15 SNR is necessary for hearing aid users to communicate successfully (Alcantara et al., 2003). With all of this information in mind hearing aid manufacturers had to put energy and manpower into developing mechanisms that would improve the SNR output for their users.

In order for the hearing aid manufacturers to develop a feature that could improve the SNR output, they had to first define what exactly noise is. Unfortunately, noise is not a discretely defined term, as much as the hearing aid manufacturers would like for it to be because it would make their jobs much easier (Bentler & Chiou, 2006). The reality is that individual preferences and perceptions often determine which sounds are desired and
which are not. Certain environments, moods and circumstances can result in different decisions regarding what is wanted or unwanted noise for an individual (Bentler & Chiou, 2006). Depending on all or a combination of some of these factors, sometimes speech, music and environmental sounds can serve as a distraction as well as an unwanted signal (Bentler & Chiou, 2006). Because of this the hearing aid industry has been given the overwhelming task of developing noise reduction algorithms that take into account the individual needs of each patient by attempting to make some generalizations about noise and how to effectively provide relief from it (Bentler & Chiou, 2006). The effectiveness of these noise reduction programs can be assessed in terms of speech intelligibility and listening comfort.

It is undeniable that the creation and addition of noise reduction algorithms to commercially available hearing aids was a necessity, but often what these programs do and how they do it remains unclear. The overarching goal of most digital noise reduction programs used in today’s hearing instruments is to reduce background noise without impacting the gain applied to speech (Alcantara et al., 2003; Bentler & Chiou, 2006; Chung, 2004; Mueller, Webber & Hornsby, 2006). This goal was established to increase effortlessness of listening, listening comfort, sound quality and even speech understanding in the presence of background noise (Alcantara et al., 2003; Mueller, Webber & Hornsby, 2006). Another goal of these programs is to create a more relaxed listening experience for the hearing aid user, and in doing so improve the effort necessary to listen (Mueller, Webber & Hornsby, 2006). It is thought that by reducing the background noise, even in situations when speech is not present, it could potentially decrease listening fatigue and improve listening awareness (Mueller, Webber & Hornsby,
Therefore, it is thought that digital noise reduction algorithms could lead to more alert and focused listeners (Mueller, Webber & Hornsby, 2006).

Another potential benefit of noise reduction algorithms is that they could make background noise less annoying, which could improve reported hearing aid satisfaction as well as ease of listening (Mueller, Webber & Hornsby, 2006). However, manufacturers have to be careful with the strategies they choose to employ and the manner in which these programs are implemented so as to ensure that the gain from speech is not also reduced (Alcantara et al., 2003). If the gain of speech is reduced as well it can lead to the users being more comfortable in a noisy environment, but could lead no improvement of intelligibility, or even less understanding, than with the signal prior to activation of the noise reduction algorithm in the first place (Alcantara et al., 2003).

Now that we have been informed as to why noise reduction algorithms were created and what their goals are, it is imperative to take a look at the research that has been done to determine if this feature is in fact effective. In 2008, Bentler et al. conducted research examining the effectiveness of noise reduction algorithms. They completed their research because there were no published reports of any available processing-based digital noise reduction strategies increasing speech understanding in the presence of background noise, yet somehow data was coming out that was discussing the benefits of such noise reduction programs (Bentler et al., 2008). The research that had been conducted at this point generally found no significant improvement when using digital noise reduction algorithms.

Bentler et al. cited the work of Walden in 2000, which examined speech understanding, sound comfort, and sound quality with directional microphones in noise
reduction ON and OFF conditions (in comparison to omnidirectional microphones). Walden’s findings indicated greater comfort with digital noise reduction ON and directional microphones than when only directional microphones were used (Bentler et al., 2008). Like Alcantara et al. they also cited the work of Boymans and Dreschler in 2000 that indicated noise reduction ON was better than OFF using self reported measures with speech recognition in car noise, aversiveness to loud sounds and traffic noise (Bentler et al., 2008). The authors also discussed the work of Ricketts and Hornsby in 2005, which looked at preference of both directional microphones and noise reduction algorithms using a laboratory based pared comparison approach. They found no benefit in terms of increased speech intelligibility, but users indicated a significant and strong preference for noise reduction ON when in the presence of high and low level background noise (Bentler et al., 2008). Based on the research that was reviewed in this article evidence suggests a strong preference and even some improvement in performance within controlled settings for noise reduction.

The extent of peer reviewed research examining the effectiveness of noise reduction algorithms has been limited to the above referenced studies. The focus recently in the realm of hearing aids has been on the differences between premium and mid-level technology. Another situation where in theory the additional features should provide great benefit, but no evidence has been collected or found to support these claims. Cox, Johnson & Xu have conducted two experiments, including a two part experiment, which evaluate some currently available premium level technology to determine if in fact there is a benefit from this increase in technology, and consequently price tag as well.
Their first experiment examining the difference between basic and premium level technology was conducted in 2014. They evaluated 25 adults with mild to moderate adult onset sensorineural hearing loss in their ability to successfully identify words in the presence of background noise (Cox, Johnson & Xu, 2014). Participant’s speech understanding was tested in a soft, average and loud noise environment. They also included questionnaires and patient diaries to determine the effectiveness of the devices. Their participant population included both new hearing aid and experienced amplification users. They used devices from two major manufacturers and included each company’s basic and premium level technology.

For the soft, average and loud listening environments there was a significant difference in the unaided v. aided scores during the evaluation. However, there was no difference in the performance of the participants when wearing basic level in comparison to premium level technology. The questionnaires reported a significant improvement in unaided v. aided listening, but their perceived amount of success in communicating during their daily lives was no different for basic or premium level technology. Quality of life changes were assessed based on the patient diaries and 96% of patients indicated that their quality of life was ‘at least a little bit better’ with amplification, however the mean rating amongst patients for their experience with amplification was closest to the rating ‘a good deal better’ (Cox, Johnson & Xu, 2014). Again, there was no difference between the ratings for basic level technology when compared to premium level technology (Cox, Johnson & Xu, 2014).

The first stage of their second round of research focuses on the patients’ perspective. Most participants indicated that their quality of life was at least “moderately
better” with the hearing aid in comparison with no amplification (Cox, Johnson & Xu, 2016). There was not a clear difference in the reported quality of life changes across the four hearing aids (two premium and two basic level hearing aids). This indicates that both technology levels, basic and premium, provided an improvement in quality of life but there was no difference in the improvement provided between the two technology levels (Cox, Johnson & Xu, 2016).

The results found that 96% of the responses for the four different hearing aid models indicated the instruments improved quality of life in comparison to no amplification, but there was no evidence that premium level technology provided more quality of life improvement than basic instruments. For each of the four hearing aid models, participants reported relatively high agreement, which is indicative of effectiveness for all models tested. The data did not however provide and evidence that the premium level technology was any better than the basic hearing aids at solving issues with speech clarity and noise discomfort, which are frequently faced by hearing aid users (Cox, Johnson & Xu, 2016).

Patient preference reports indicated equally divided preferences between the premium and basic level instruments. There was a trend observed in the results that indicated the second pair of devices was rated to be the primary preference over the first, regardless of technology. This was the case even though both technology level and brand were variables that were counterbalanced. Previous experience with hearing aids was not a controlled variable in the study, which allowed some comparison to be made between new and previous HA users. Neither group indicated a significant difference in quality of life changes between premium and basic level technology (Cox, Johnson & Xu, 2016).
There was also no significant difference between the groups in terms of preference regarding technology level (Cox, Johnson & Xu, 2016).

As a whole, participants did not prefer the premium level instruments over the basic technology. There was an identical pattern of statistical results when the premium and basic level hearing aids from brand A and brand B were compared separately. There was no difference between the two technology levels in terms of the efficiency on users daily life. Data from the two major hearing aid manufacturers used in the study were evaluated from the point of view of standard hearing aid users and what their daily lives entailed. It appears that the considerably higher dollar amount tied to deemed premium level technology did not result in a realistic increase in the effectiveness of the device in comparison to basic level technology (Cox, Johnson & Xu, 2016). Their hope is that these findings lead to more cost-conscious and effective hearing aid recommendations and improved access to successful, more affordable, hearing health care for current clinicians (Cox, Johnson & Xu, 2016).

The second part of the research recently conducted by Cox, Johnson & Xu focused on speech understanding and listening effort. Unaided listening regularly led to worse scores in comparison to each aided listening condition, across all four instruments (Johnson, Xu & Cox, 2016). Among the four aided conditions, the differences were minimal. Speech intelligibility was greatly impacted by whether the participant was aided or not, in the soft, average and loud environments (Johnson, Xu & Cox, 2016). There was no difference between premium level and basic level hearing aids in terms of speech intelligibility (Johnson, Xu & Cox, 2016). Unaided listening regularly led to less success in comparison to each aided listening condition, across all four instruments. Among the
four aided conditions, the differences were minimal. This suggests that amplification alone greatly increases the perceived occurrence of success in terms of speech intelligibility (Johnson, Xu & Cox, 2016).

Listening effort was reported to improve for both brand A and B for both premium and basic level technology (Johnson, Xu & Cox, 2016). Users perceived aided speech intelligibility benefit in the real world was not significantly influenced by technology level. Users also perceived listening effort in the real world was not significantly influenced by technology level (Johnson, Xu & Cox, 2016). The findings of this study are consistent with prior research that was conducted and found that speech intelligibility and listening effort are improved with amplification. This improvement was noted in the laboratory along with in everyday life situations. For both brands of hearing aids, for both technology levels, no difference was found in either the laboratory or everyday situations in terms of speech intelligibility or listening effort outcomes. Data from participant diaries indicated that the technological advancements that are incorporated into premium level technology were not noticeable or perceived to be of greater value than basic level technology in regards to communicating on a daily basis (Johnson, Xu & Cox, 2016).

This research is necessary for a variety of reasons and the authors of the current study are not the only ones who feel this way; similar feelings have been expressed in several other publications. Bentler wrote in the 2005 publication of her research examining the effectiveness of directional microphones and noise reduction schemes in hearing aids that she couldn’t find enough research to truly prove the effectiveness of noise reduction schemes. She called for more research to be done to prove clinical
effectiveness (Bentler, 2005). Mueller, Webber & Hornsby expressed frustration about the fact that there has been a great deal of written information discussing the potential benefits of DNR regarding speech comprehension and listening comfort, but there is very little published evidence that actually supports these claims (Mueller, Webber & Hornsby, 2006). This was written in their 2006 paper examining the effects of digital noise reduction on the acceptance of background noise.

However, the greatest call to the field for more clinical research evaluating the claims made by manufacturers was made by Cox, Johnson & Xu in their two part publication that evaluated the impact of hearing aid technology on outcomes in daily life in 2016. They stated in their research that a recurrent theme is the opinion that hearing aids do not perform at a level to justify the price tag associated with them. Research indicates that patients often conduct a cost-benefit analysis to aid in deciding the true value of hearing aids (Cox, Johnson & Xu, 2016). These cost-benefit analyses have shown that instruments that deliver more benefit for a particular cost or the same benefit at a smaller price point are perceived to offer a greater value. This can be taken to mean that hearing aids that provide more value per unit of cost to the patient are more likely to be accepted. Although cost is not the only factor that determines whether or not a hearing aid will be considered valuable and accepted by a patient, it is a major contributor to that decision (Cox, Johnson & Xu, 2016). Interestingly, it is known that perceived cost-benefit outcomes are important to patients in determining the value of hearing aids; very little research has been conducted in this area as well.

Every manufacturer today presents their instruments in “families” which include three or four models, each with progressively more sophisticated technology levels. As
the technology levels increase, so does the associated price tag with that instrument. The hearing aids that are available currently have digital signal processing features that are created to increase outcomes in a variety of listening situations. One of these is digital noise reduction, which was designed to decrease the gain of unintended noises. The lower level technology within a “family” still included all of the features currently available as part of digital signal processing but the premium levels are said to house more complex, automatic, and adaptive versions of these same processing features along with some features that are not even offered in the more basic technology levels (Cox, Johnson & Xu, 2016).

With this in mind, it would seem obvious to assume that the more complex, adaptive, and automatic signal processing features within a hearing aid there are, the greater the benefit the user would gain throughout their daily life. If this is the case, the cost-benefit analysis would at least stay constant, with the potential for an increase, for these premium level devices. While this all sounds nice and logical based on the theory behind premium level technology, unfortunately increased real life benefit from using this technology has not been found in independent research thus far (Cox, Johnson & Xu, 2016). The self reported needs of some patients may suggest a potential benefit from premium level technology, while others may benefit in terms of experience and cost from more basic level technology (Cox, Johnson & Xu, 2016).

It has been suggested that this higher level technology provides greater access to speech cues given the advanced signal processing features, which would also reduce the effort required to listen in challenging environments and would consequently result in less fatigue; unfortunately this theory has not yet been proven. Based on the foundation
that premium level technology has been created on, it is not surprising that it is assumed
premium level technology would further decrease listening effort in comparison to basic
level technology. Thus far, the research that has been conducted to evaluate this theory
has not found any better or improved listening effort with premium level technology in
comparison with basic level hearing aids (Johnson, Xu & Cox, 2016).

To date there is little independent research that has explored if more advanced
signal processing actually provides more advanced outcomes in specific listening
environments. In order for practitioners to make evidence grounded recommendations
independent research needs to be conducted to evaluate premium and basic level
technology in not only laboratory but also real world situations. The focus on this
research needs to be improvement in speech intelligibility and listening effort (Johnson,
Xu & Cox, 2016). Hearing aids that are identified as premium level technology, and
therefore more advanced, are associated with a much higher price tag than basic level
technology. With this higher price tag it is assumed these instruments will provide greater
improvements in speech understanding and listening effort. However, the little research
that has been done in this area did not find this to be the case. Instead it was found that
amplification is significantly better than no amplification in these areas, but in all the
facets that data was collected and analyzed there was no difference between premium and
basic level technology (Johnson, Xu & Cox, 2016).

Unfortunately, clinicians do not have any guidelines grounded in scientific
evidence to help them determine which patients fit into which category. Instead they have
to rely on claims made by manufacturers, which are frequently unverified, to decide
which technology level to recommend to patients. Often times patients will ask about the
difference in technology levels and clinicians are forced to present the claims manufacturers have made or the differences in features between the two, but that rarely translates to differences the patients will perceive in their daily life. This is not an acceptable manner to determine which technology level is recommended to an individual (Cox, Johnson & Xu, 2016). It is imperative that practitioners have access to real world improvements their patients will experience with each technology levels and that these improvements are based on scientific evidence in order to make sound recommendations to patients (Cox, Johnson & Xu, 2016).

There have been many studies that examine if there is an improvement in speech understanding and perception with noise reduction ON. The results have been marginal at best, most indicating a perceptual improvement when digital noise reduction is enabled according to patient reports, but performance on speech related tasks does not indicate any improvement with noise reduction ON in comparison to OFF. However, there haven’t been any studies that examine if the digital noise reduction algorithms objectively do what they are supposed to do, which is why this study is necessary. The findings of the current study will contribute to the scare independent research that is currently available to aid clinicians in making recommendations for their patients regarding which technology level best suits their needs, recommendations that need to be based on sound scientific evidence.

This study aims to answer the following research question by completing this experiment: Will there be a significant electroacoustic difference in the advanced signal processing features (digital noise reduction) of mid level and premium level hearing aids from major manufacturers
Methods:

Hearing Instruments:

Premium and mid-level digital hearing aids from four major manufacturers were obtained and programmed for a bilateral mild to moderately severe sloping sensorineural hearing loss using the manufacturer’s proprietary fitting formula. Each hearing aid was programmed for noise reduction (NR) ON and OFF with every other feature disabled, or minimized to the best of our ability based on how much control each manufacturer gives the programmer. Hearing aid programming was verified, and each hearing aid was tested twice for reliability. A new battery was used for each recording and was tested prior to recording to ensure that it was in optimal working condition; 1.4 mV was the cut off criterion for each battery, if the measured voltage was less than 1.4 mV it was not used in this study. The most current mid-level hearing aid was not available from manufacturer B at the time of testing. Hence, their mid-level technology from the immediate past generation was included in this study.

Test Stimuli:

The level of noise reduction (gain reduction) was measured using two types of custom stimuli that were created by Hanline & Rout in 2008. The first test stimuli used in this study was specially constructed to assess if NR algorithms can decrease the gain in a frequency region encompassing a noise stimulus. ICRA noise was notch filtered and this notch was filled with steady-state broadband noise that was frequency-shaped similar to ICRA noise. The location (center frequency) and width of the band rejection notch were varied. In total, three different bandwidths of steady-state noise (one-third octave, one octave, and two octave) were embedded at four different frequencies (0.5, 1, 2, and 4
kHz) resulting in twelve new stimuli. Each stimulus was around one minutes in duration. The overall RMS of the stimuli were equalized.

In addition, a 30 second steady state speech shaped noise was included to evaluate the attack time and overall gain reduction of each NR algorithm. The overall RMS of the stimuli were equalized. With the twelve ICRA notch filtered stimuli and the steady state speech shaped noise, a total of 13 stimuli were used in this experiment. Figure 1 displays a spectrogram of the ICRA noise, Figure 2 displays the spectrogram and frequency analysis of ICRA noise with a two octave notch centered at 2000 Hz, and Figure 3 displays the spectrogram and frequency analysis of ICRA noise with the embedded two octave steady-state noise centered at 2000 Hz.
Recording Procedure:

The 13 stimuli were streamed from the hard drive of a PC through a RussSound 1200 amplifier and presented from a Tannoy System 600 sound field speaker at 65 dB SPL in a Xm by Xm double walled sound booth. Prior to every data recording session, the stimuli were calibrated and confirmed to be 65 dB SPL at KEMAR’s ear level using a Quest 1700 Precision Sound Level Meter. The sound level meter was set to analyze sound in slow response mode, in SPL, with A-weighting, and in a 40-100 dB range. The programmed hearing aid was mounted on KEMAR, who was placed at 1 meter from the speaker, with a closed dome to attempt to reduce any sound waves from escaping. The output of each hearing aid was recorded with an ER-11 ½-inch microphone coupled with a Knowles Electronics DB-100 coupler and digitized using Sound Forge, a commercially available sound editing program. Sound Forge was also used in the data analysis of this experiment.

During every recording each stimulus was recorded twice, to further enhance and ensure the reliability measures of this project. For example, the 1/3 octave band at 500 Hz
stimulus was recorded twice on the initial recording, and twice during the second recording, creating four separate recordings that were available and utilized in the data analysis. The recordings were saved to the hard drive of the laptop used during the data collection and then were transferred to an external hard drive and finally a Desktop in the lab for analysis. This also ensured that if something were to happen to the laptop used during testing that all of the previously recorded data would not be lost.

**Data Analysis:**

After each hearing aid was tested twice for reliability, the recorded output was examined for analysis. The overall recorded dB for each stimuli was compared in the noise reduction ON and OFF condition, and the difference in dB was deemed the overall noise reduction. The amount of the overall noise reduction for each stimuli was compared to the second test for reliability to determine how similar the two recordings were, as shown by the error bars in the graphs found in the Results section.
Results:

The results of this experiment were analyzed in two different ways. First, the overall noise reduction was examined by analyzing the data collected from the one steady state stimuli used in this study, across the different hearing aids. Then, the frequency specific noise reduction was analyzed by examining the data collected from the twelve different frequency specific stimuli across the different hearing aids.

The data used to analyze the results collected from the steady state stimuli can be seen in below in Figures 4 and 5.

Figure 4: Attack time of the noise reduction algorithm in response to a steady state noise. Error bars represent ±1 SD. The panel of waveforms on the right show representative attack times for mid-level technology from each manufacturer.
Figure 5: The overall noise reduction between premium and mid-level hearing aids was analyzed with a paired comparison t-test.

There was no significant difference between technology levels \( t(7) = 0.695, p = 0.51 \). Since the hearing aids from Oticon were from two different platforms, another analysis was performed without that data. However, significance was not achieved \( t(5) = 1.596, p = 0.17 \).

The overall noise reduction between premium and mid-level hearing aids was analyzed with a paired comparison t-test. There was no significant difference between technology levels \( t(7) = 0.695, p = 0.51 \). Since the hearing aids from Oticon were from two different platforms, another analysis was performed without that data. However, significance was not achieved \( t(5) = 1.596, p = 0.17 \).
Figure 6. Frequency-specific noise reduction in response to the steady-state stimuli. Each panel shows data from an individual manufacturer. Higher values indicate greater amount of noise reduction.

The data used to analyze the results collected from the frequency specific stimuli can be seen below in Figure 7.
Figure 7: Frequency specific gain reduction in response to the ICRA noise with embedded steady state noise. Positive numbers indicate greater noise reduction. Note: X-axis in all graphs indicates hearing instrument model.

A 2x3 ANOVA was performed with technology (2 levels) and noise bandwidth (3 levels) as within-subject factors. There was a significant main effect of technology level [$F_{(1,12)}=9.49$, $p=0.01$], and a significant interaction between technology level and noise bandwidth [$F_{(2,24)}=6.34$, $p=0.006$]. There was also a significant main effect of noise bandwidth [$F_{(2,24)}=4.53$, $p=0.02$].
Discussion:

The findings of this study suggest that there is no difference between the noise reduction efficiency of a premium level hearing aid when compared to a mid-level instrument at reducing steady state background noise. Since the mid-level instrument from Oticon was from a previous processing chip and technology generation data from Oticon as a whole (mid-level and premium) was removed from analysis and another t-test was performed; significance was still not achieved. This suggests that in a situation where a great deal of background noise is present and that noise is made up of essentially the same acoustic component, known as steady state background noise, that a mid-level and premium level hearing aid would perform comparably in terms of its ability to reduce the background noise. Clinically, this information can be used by professionals when determining which level of technology is appropriate for a patient. These results indicate that for patients that find themselves in a large amount of background noise, without speech stimuli present, premium level technology is not necessary as a mid-level instrument would be just as effective in meeting their needs regarding reducing background noise.

The results of the frequency-specific stimuli tell a different story however. The data indicated that there was a significant difference in the noise reduction capabilities of a mid-level and premium level hearing instrument when the background noise included both speech and background noise, as simulated by the ICRA stimuli. There was also a significant interaction between technology level and noise bandwidth as well as a significant main effect of noise bandwidth. These findings are not shocking in the least bit as it is expected that the larger the bandwidth of noise embedded within the signal, the
greater the proportion of the signal is made up of noise, the easier it will be for the instrument to detect the presence of noise and therefore effectively reduce it. These results suggest that for patients who find themselves in more complex listening environments, those that include both speech and background noise, that premium level technology may be of benefit to them.

Looking at the data from the frequency specific stimuli it is apparent that different manufacturers are employing different strategies when it comes to noise reduction. Overall it seems all manufacturers provided a great, if not the greatest, amount of noise reduction when the notched noise was inserted at 500 Hz. This finding is not surprising as it is well known that most background noise is low frequency in nature so it seems logical that all manufacturers would emphasize low frequency background noise in the development of their noise reduction algorithms. It appears that regardless of the frequency of the inserted noise that Starkey takes a more comprehensive and complete approach to noise reduction as their instruments provided the greatest amount of noise reduction across the board, regardless of frequency. On the other hand, it appears that while Oticon overall did not provide a large amount of noise reduction in general, the most amount of reduction was seen in the low frequencies. As far as the high frequencies go, almost no noise reduction exists and even in some cases an increase in gain was seen. This data indicates that their approach to noise reduction is very different from that of Starkey’s; they appear to want to focus more on insuring audibility as opposed to tackling noise and are doing that through amplification of those frequencies important for speech, 2000-4000 Hz.
This study also examined the overall attack time of noise reduction for steady state stimuli. Attack time refers to the amount of time it takes for the hearing aid to detect the presence of noise and engage the noise reduction algorithm. Yet again Starkey stands out, but not necessarily a positive manner this time. The other manufacturers engaged the noise reduction feature for both of their mid-level and premium technology devices in fewer than 10 seconds, the majority less than 5 seconds. Starkey on the other hand took more than 10 seconds for the Musei1600 and upwards of twenty seconds for the i2400 instrument to reduce the noise. Inversely however, Starkey technology provided the greatest amount of overall noise reduction for steady state noise.

The findings of this study are beneficial to clinicians because they provide empirical evidence from a third party source regarding the capabilities of noise reduction programs from four major manufacturers in the hearing aid industry today. Professionals will be able to look at this data and obtain a better understanding as to how each individual manufacturer’s algorithm works and ultimately assist them in determining which technology level is appropriate for their patients.

As this study did not include any human subjects it is difficult to compare the results from this experiment to those completed previously evaluating noise reduction algorithms; that is one of the limitations of this experiment. The data we found is important and necessary as so little objective literature exists regarding the efficiency of these algorithms, but without human subjects and their experiences with the instruments it is difficult to give the data found proper significance. This study found that Starkey’s overall attack time for steady state noise is the longest but once activated provided 24+ dB of noise reduction. So What? We know that the noise reduction algorithm is definitely
reducing the noise, but is an attack time that slow with that much noise reduction considered pleasing to patients subjectively? That is the information we need to add to the results from this study to have truly impactful literature to introduce to the field. Once we have that information to add to the results obtained from this study clinicians will have all the tools necessary to make technology recommendations that are grounded in strong evidence based practices.
Conclusion:

The goal of this study was to objectively analyze the effectiveness of the noise reduction features in premium vs. mid-level technology in an effort to provide clinicians with the tools to necessary to make appropriate technology recommendations for their patients, and ultimately determine if the extra cost associated with premium level technology is warranted. Simply put, this study was designed to determine if there is a difference between premium and mid level technology. This study evaluated only one feature of current hearing aids on the market today, noise reduction, and obviously the efficiency of a sole component of these devices does not determine their worth or effectiveness. However, we do know that understanding speech in background noise is a problem for many people and the desire to improve that is why many individuals decide to give amplification a try. As speech in noise is a topic of importance to many hearing aid users, it seemed appropriate to focus on noise reduction for the purposes of this study.

After looking at the data it turns out answering the question “Is there a difference between mid-level and premium technology regarding noise reduction capabilities?” is not as simple as posing the question. When analyzing the data collected from the steady state stimuli, no there is not a significant difference between the performance of mid-level and premium level technology. The data collected from the frequency specific stimuli indicate that there is a significant difference between the noise reduction ability of premium vs. mid-level technology. So what does this mean? It means that for some patients’ premium level technology may be of benefit to them from the perspective of noise reduction capabilities; most likely those patients who are in more complex listening environments with a wide frequency range of background noises.
In reality, the results from this study alone cannot answer that question. The follow-up to this study will include subjective data from human subjects, which is necessary to produce a more complete picture about noise reduction effectiveness and the difference in performance between mid-level and premium level technology. Once that data is obtained and analyzed in combination with the data that has been collected from this study, a vast amount of literature and knowledge will be available to clinicians to aid them in making technology recommendations for their patients. Those recommendations, thanks to the results from this study and the studies to follow, will be based on empirical evidence (as they should be) as opposed to misguided claims from manufacturers or the desire to meet their monthly sales quota. Studies like this are incredibly necessary in order to ensure that professionals in the field are treating their patients with the best practices possible. More independent research is needed to give clinicians the resources to make informed decisions regarding treatment plans, decisions that they can feel good about because they know that they are backed by evidence based practices.
**Literature Review:**

Noise reduction is a familiar term when discussing digital hearing aids today however, little is talked about regarding why it was created, what it is and how it actually works. Hearing aids needed to include noise reduction algorithms due to the fact that the main complaint amongst hearing aid users who were fit in the early 2000s was that it was difficult to focus on speech in the presence of background noise (Alcantara et al., 2003). These users were typically fit with omnidirectional microphone patterns and without noise reduction features (Alcantara et al., 2003). Instruments that were fit in this manner were effective at enhancing speech in quiet environments, but when these hearing aids were used in the presence of background noise it actually resulted in amplification of the background noise along with speech, leading to no improvement of the signal-to-noise-ratio (SNR) (Alcantara et al., 2003). This often led to reduced intelligibility as the background noise was amplified as well, which propagated an upward spread of masking (Alcantara et al., 2003). It is a well known fact that in public places the SNR of conversation tends to be around +5 to +10 SNR, however research indicates that +10 to +15 SNR is necessary for hearing aid users to communicate successfully (Alcantara et al., 2003). With all of this information in mind hearing aid manufacturers had to put effort and time into developing mechanisms that would improve the SNR output for their users.

In order to develop a mechanism to improve the SNR output, it is necessary to first define what exactly noise is. Unfortunately, noise is not a discretely defined term, as much as the hearing aid manufacturers would like for it to be because it would make their jobs much easier (Bentler & Chiou, 2006). The reality is that individual preferences and perceptions often determine which sounds are desired and which are not and certain
environments, moods and circumstances can result in different decisions regarding what is wanted or unwanted noise for an individual (Bentler & Chiou, 2006). Depending on all or a combination of some of these factors, sometimes speech, music and environmental sounds can serve as a distraction as well as an unwanted signal (Bentler & Chiou, 2006). Because of this the hearing aid industry has been given the overwhelming task of developing noise reduction algorithms that take into account the individual needs of each patient by attempting to make some generalizations about noise and how to effectively provide relief from it (Bentler & Chiou, 2006). The effectiveness of these noise reduction programs can be assessed in terms of speech intelligibility and listening comfort.

It is undeniable that the creation and addition of noise reduction algorithms to commercially available hearing aids was a necessity, but often what these programs do and how they do it remains unclear. The overarching goal of most digital noise reduction programs used in today’s hearing instruments is to reduce background noise without impacting the gain applied to speech (Alcantara et al., 2003; Bentler & Chiou, 2006; Chung, 2004; Mueller, Webber & Hornsby, 2006). This goal was established to increase effortlessness of listening, listening comfort, sound quality and even speech understanding in the presence of background noise (Alcantara et al., 2003; Mueller, Webber & Hornsby, 2006). Another goal of these programs is to create a more relaxed listening experience for the hearing aid user, and in doing so improves the effort necessary to listen (Mueller, Webber & Hornsby, 2006). It is thought that by reducing the background noise, even in situations when speech is not present, it could potentially decrease listening fatigue and improve listening awareness (Mueller, Webber & Hornsby,
Therefore, it is thought that digital noise reduction algorithms could lead to more alert and focused listeners (Mueller, Webber & Hornsby, 2006).

Another benefit of noise reduction algorithms is that they could potentially make background noise less annoying, which could improve reported hearing aid satisfaction as well as ease of listening (Mueller, Webber & Hornsby, 2006). However, manufacturers have to be careful with the strategies they choose to employ and the manner in which these programs are implemented so as to ensure that the gain from speech is not also reduced, only noise should be the target (Alcantara et al., 2003). If the gain of speech is reduced as well it can lead to the users being more comfortable in a noisy environment, but for the trade off of no improvement of intelligibility, or even less intelligibility, than the signal prior to activation of the noise reduction algorithm in the first place (Alcantara et al., 2003).

It has been established that digital noise reduction programs have been developed to take advantage of the temporal and spectral dissimilarities between speech and noise (Chung, 2004). It is important to note though that noise reduction algorithms differ from speech enhancement programs in that noise reduction focuses on decreasing the interference of noise, while on the other hand speech enhancement programs are developed to enhance the difference between consonants and vowels (Chung, 2004). It is also difficult to learn much about digital noise reduction algorithms because all programs are proprietary to each individual manufacturer so there are field wide differences amongst signal detection methods, decision rules, and time constants (Bentler et al., 2008; Chung, 2004). The commonality amongst them all however is the recognition of the modulation patterns within the incoming signal to deduce whether speech is present.
or absent, as well as to approximate the output SNR of the microphone (Alcantara et al., 2003; Bentler et al., 2008; Chung, 2004; Mueller, Webber & Hornsby, 2006).

Now that we have been informed as to why noise reduction algorithms were created and what their goals are, it is imperative to understand how these programs work. Surprisingly, noise reduction was actually introduced to hearing aids in the 1970s (Bentler & Chiou, 2006). At this time, hearing aids were still using analog signal processing and these instruments had a tone switch that was created to switch on a low-frequency filter, which would decrease the low frequency gain of background noise (Bentler & Chiou, 2006). Other early versions of noise reduction were advertised to incorporate adaptive filtering, adaptive compression and low-frequency compression but did not actually deliver the projected increase in speech understanding in the presence of background noise (Bentler & Chiou, 2006). Many of these early noise reduction features only applied gain reduction in the low frequency region, which would keep the higher energy low frequency sounds from triggering the compression unit in the noise reduction program and decreasing the gain across the entire frequency range or making the chance of upward spread of masking more likely (Bentler & Chiou, 2006). While in theory this approach to noise reduction seems logical, it does not take into account that each person has a different opinion regarding which sounds are annoying and the sounds that are rated as annoying cannot always be anticipated by on their spectral and temporal characteristics alone (Bentler & Chiou, 2006).

Early noise reduction schemes were only implemented in a single channel, the gain reduction was limited to the abilities of the analog filters that were used at the time, and the amount of gain reduction used was dependent on input level (Bentler & Chiou,
As the creation of digital noise reduction algorithms began, it also led to more complicated programs that utilized decision rules that were able to define what noise is, how much gain reduction is necessary, and what frequency regions the attenuation should be applied to (Bentler & Chiou, 2006; Chung, 2004; Mueller, Webber & Hornsby; 2006). The Wiener filter was used in the early stages and it requires that the spectra of the intended speech signal and the noise have values that are stationary, a principle that is rarely ever met in the real world (Bentler & Chiou, 2006; Chung, 2004). Spectral subtraction was also used, in which the short-term noise spectrum is obtained during the pauses in speech and is then subtracted from the speech and noise spectrum after the speech is presented again (Bentler & Chiou, 2006; Chung, 2004).

While these early digital noise reduction schemes were innovative for their times, they were not effective. We live in a world that is time-variant, where speech has identified temporal patterns known as modulations, therefore noise reduction programs had to move from analog filtering of targeted frequency bands to digital filtering that relies on the temporal features of the environmental sounds (Alcantara et al., 2003; Bentler & Chiou, 2006). One of the biggest discoveries and components that digital noise reduction schemes rely on is modulation rate to distinguish speech from noise. Speech is known to have fewer modulations but has a greater depth of modulation in comparison to most noise (Bentler & Chiou, 2006; Chung, 2004). Manufacturers used this knowledge as a basis for the development of their new digital noise reduction programs. For example, decisions rules were implemented that stated for modulation frequencies of less than 10 Hz gain reduction is not activated, but for higher modulation rates gain reduction from 6-8 dB will be applied. These rules can be applied to one, a few or all frequency channels in
a hearing aid (Alcantara et al., 2003; Bentler & Chiou, 2006; Chung, 2004). Other manufacturers created rules based on modulation depth as opposed to rate, however many have decided to utilize rules on the basis of both modulation rate and depth (Alcantara et al., 2003; Bentler & Chiou, 2006; Chung, 2004).

The amount of gain reduction that is applied varies greatly based on different manufacturers even though they all have the same goal, to ensure the gain for speech is not reduced (Bentler & Chiou, 2006). Even though most professionals would claim that greater amounts of attenuation for pure noise is better, there needs to be a fine balance in terms of gain reduction (Bentler & Chiou, 2006). Enough attenuation needs to be applied so that unwanted noises are reduced but not so much gain reduction that speech intelligibility is impacted. This is why some manufacturers have created rules determining a maximum amount of gain reduction that can be applied so as to try to accommodate the necessary balance (Bentler & Chiou, 2006).

One method to address this is to set the amount of gain reduction to be inversely proportional to the articulation index of the frequency region (Chung, 2004). This is done on the basis that as the weightings of the articulation index increase, the importance of the corresponding frequency channel increases as well. This means that less gain reduction should be applied to those channels so that speech understanding is not degraded (Chung, 2004). Other manufacturers employ gain reduction to only certain frequency regions, and their corresponding channels, based on the importance of the speech information present in those areas (Chung, 2004). For example, a manufacturer may chose to only reduce gain in frequency channels below 1kHz and above 2 kHz, with the assumption that the frequencies between 1-2kHz are essential to speech intelligibility.
and gain reduction should not be applied irrespective of the detected modulation depth at those frequencies (Chung, 2004).

Another approach to taken by some companies may be to allow the clinician to determine the maximum amount of gain reduction that can be applied in each frequency channel (Chung, 2004). The greater or stronger the professional sets the noise reduction to be, the closer the program comes to applying the maximum amount of noise reduction possible (Chung, 2004). It is important to note however that even when the maximum amount of noise reduction is applied in or across frequency channels, it does not impact the frequency weighting of that specific channel (Chung, 2004).

Typically, there are four time constants that are incorporated within multichannel adaptive noise reduction algorithms: the engaging/adaptation/attack time, the speed of gain reduction, the disengaging/release time and the speed of gain recovery (Bentler & Chiou, 2006, p.72; Chung, 2004). The engaging/adaptation/attack time is the time it takes the noise reduction to implement the gain reduction necessary once the program detects the presence of noise (Bentler & Chiou, 2006; Chung, 2004). The speed of gain reduction is the time it takes for the noise reduction to reach maximum gain reduction once gain reduction is initiated (Bentler & Chiou, 2006; Chung, 2004). The disengaging/release time is the time it takes the noise reduction to gain starts to recover once the program detects noise is no longer present in that specific channel (Bentler & Chiou, 2006; Chung, 2004). Finally, the speech of gain recovery is the time it takes the hearing aid to reach 0 dB gain once gain recovery is initiated (Bentler & Chiou, 2006; Chung, 2004).

It is difficult to define exactly what these time constants should be due to the fact that those components vary depending on the noise signal (Bentler & Chiou, 2006;
Chung, 2004). If the noise reduction program has a fast attack and release time or fast gain reduction or recovery times, the stops or fricative consonants within transient speech may be assumed to be noise, and therefore be suppressed (Bentler & Chiou, 2006; Chung, 2004). On the other hand, if a digital noise reduction algorithm has slow time constants, sudden or brief changes in the environment may not be detected and the appropriate gain may not be applied (Bentler & Chiou, 2006; Chung, 2004).

An issue that all manufacturers face is determining at what point the digital noise reduction will become activated; if it is set too low it could limit speech audibility and if it is set too high it could impact listening comfort (Bentler & Chiou, 2006). This activation threshold works in a manner that if a modulation depth is detected within a channel that suggests noise is present gain reduction is only applied to that channel if the input level of the signal exceeds 50-60 dB (Chung, 2004). The amount of the gain reduction that is applied to that frequency channel will also increase as the level of the incoming signal is increased as well (Chung, 2004). This method was developed on the basis that noise reduction is unnecessary when an individual is in quiet or in the presence of low level noise, but noise reduction schemes are necessary when higher levels of noise, or a nosier environment, is detected (Chung, 2004). Some have based this threshold on the articulation index as a way to attempt to find a happy medium between the two ends of the spectrum (Bentler & Chiou, 2006).

Based on their construct, multichannel adaptive noise reduction algorithms should exhibit superior performance when there are spectral differences between speech and noise (Chung, 2004). This is because if the noise is only present in a discrete frequency region, the noise reduction program reduces the gain of the instrument in that specific
region without affecting the speech components present in other frequency regions (Chung, 2004). A frequent finding of experiments testing noise reduction algorithms is that no benefit for speech intelligibility is observed in the presence of broadband noises, like the car (Chung, 2004). This is because if the algorithm reduces the gain in frequency regions where noise is prominent, it will also reduce the understanding of speech information in that channel (Chung, 2004). Therefore speech intelligibility is never improved (Chung, 2004). Benefit can be seen regarding speech understanding or listening comfort in the presence of steady state noise, but is not typically seen in noise that encompasses modulation patterns similar to speech (Chung, 2004). This is due to the fact that multichannel adaptive noise reduction algorithms rely on recognizing noise interfering with speech based on the modulation pattern (Chung, 2004). If the noise present is composed of speech or has modulation patterns that mimic speech, and is competing with a desired speech signal, the program cannot determine which is the speech and which is noise (Alcantara et al., 2003; Chung, 2004). Generally, the greater the difference in the acoustic makeup of the speech and noise, the more efficient the digital noise reduction scheme can be (Chung, 2004).

Some manufacturers have implemented synchronous morphology techniques in their digital noise reduction schemes; this bases gain reduction rules off of co-modulation instead of on the modulation features of speech (Bentler & Chiou, 2006; Chung, 2004). The logic behind the design of this type of digital noise reduction is that the energy of speech sounds is co-modulated due to the opening and closing of the vocal folds during speech production of vowels and voiced consonants (Chung, 2004). The rate of co-modulation of speech is also known as the fundamental frequency of an individual’s
voice, which typically ranges from 100-250 Hz for adults and can be as high as 500 Hz for children (Bentler & Chiou, 2006; Chung, 2004). The contrast is created because noise, is rarely ever co-modulated (Bentler & Chiou, 2006; Chung, 2004). The unit responsible for signal detection within the hearing aid is continuously monitoring the incoming signal at high frequency bands for synchronous energy at the rate of fundamental frequencies of human voices (Chung, 2004). The goal of this is to improve the listening comfort when speech is not present, but it does not provide any benefit in either category when speech is detected in the presence of background noise or if the competing signal is made up of speech (Chung, 2004).

In theory digital noise reduction algorithms seem like an effective solution to complaints from users about trying to communicate in the presence of background noise, but like many things theory does not always translate to success in the real world. Fortunately, research has been done testing the effectiveness of these noise reduction schemes in daily life situations. Alcantara et al. conducted a study in 2003 that examined the noise reduction algorithm from the hearing aid manufacturer Phonak, called Fine-scale Noise canceller (FNC), in the Claro 21 dAZ device. This hearing aid had 20 frequency specific channels. The FNC estimated the SNR in each channel and reduced the gain in channels with center frequencies below 1 kHz and above 2kHz when the SNR estimate reported a poor SNR (Alcantara et al., 2003). The gain was not reduced for channels with center frequencies between 1 and 2kHz, as those are deemed to be the most important frequencies for speech intelligibility according to the American National Standards Institute in 1997 (Alcantara et al., 2003). FNC determined the SNR on the basis of the estimated modulation rates and depths in each channel (Alcantara et al.,
2003). The lower the depth and rate of modulation, the lower the SNR is projected to be leading to a greater amount of gain reduction (Alcantara et al., 2003).

Based on the design of FNC, it is anticipated the benefit from enabling the FNC feature would vary based on the noise used in the study, or present in real life (Alcantara et al., 2003). In theory, steady state noise with spectral dips would lead to channels dominated by noise, which would lead to gain reduction, and other channels dominated by speech, which would be left untouched (Alcantara et al., 2003). It is expected that in these situations that across frequency masking effects would be reduced, leading to improved speech intelligibility (Alcantara et al., 2003). When used with noise comprised of modulated speech shaped information, FNC would not be expected to work well (Alcantara et al., 2003).

In this study speech reception thresholds and rating scales of user satisfaction were completed after a 3-month period (Alcantara et al., 2003). The results did not find statistically significant improvements in either speech intelligibility or subjective satisfaction when FNC was turned on (Alcantara et al., 2003). On the other hand, it was noted that the presence of FNC did not appear to reduce speech intelligibility or satisfaction either (Alcantara et al., 2003). The authors’ thought based on the design of FNC that it would effectively reduce steady speech shaped noise with 4-ERB dips, but they did not find that to be the case (Alcantara et al., 2003). This may be due to the fact that the reduction in across-frequency masking produced by the FNC was counterbalanced by loss of speech information from the attenuated bands (Alcantara et al., 2003).
Research conducted by Boymans and Dreschler in 2000 found similar results. Their experiment found no significant difference in noise reduction ON or OFF performance, but 7 of the 16 subjects in the study chose to keep the noise reduction feature activated in the hearing aids they took home after the study was completed (Alcantara et al., 2003). Even though no benefit of FNC was found, the hearing aid itself did provide great improvements in the ability of the users to understand speech in noise, in comparison to unaided listening, even though performance levels were still under that of normal listeners (Alcantara et al., 2003).

In 2008, Bentler et al. also conducted research examining the effectiveness of noise reduction algorithms. They completed their research because there were no published reports of any available processing-based digital noise reduction strategies increasing speech understanding in the presence of background noise, yet somehow data was coming out that was discussing the benefits of such noise reduction programs (Bentler et al., 2008). The research that had been conducted at this point generally found no significant improvement when using digital noise reduction algorithms.

Bentler et al. cited the work of Walden in 2000, which examined speech understanding, sound comfort, and sound quality with directional microphones in noise reduction ON and OFF conditions (in comparison to omnidirectional microphones). Walden’s findings indicated greater comfort with digital noise reduction ON and directional microphones than when only directional microphones were used (Bentler et al., 2008). Like Alcantara et al. they also cited the work of Boymans and Dreschler in 2000 that indicated noise reduction ON was better than OFF using self reported measures with speech recognition in car noise, aversiveness for loud sounds and traffic noise.
The authors also discussed the work of Ricketts and Hornsby in 2005, which looked at preference of both directional microphones and noise reduction algorithms using a laboratory based paired comparison approach. They found no benefit in terms of increased speech intelligibility, but users indicated a significant and strong preference for noise reduction ON when in the presence of high and low level background noise (Bentler et al., 2008). Based on the research that was reviewed in this article evidence suggests a strong preference and even some improvement in performance within controlled settings for noise reduction, however no data before has isolated these findings from directional microphones; that was the purpose of Bentler et al.’s study (Bentler et al., 2008).

They also aimed to determine if there is an optimally effective attack time for noise reduction performance and user preference, as well as examining the impact of visual cues on performance (Bentler et al., 2008). This was of interest because previous studies indicated improved comfort in noise reduction ON conditions, and as many hearing aid users benefit from visual cues, if noise reduction ON and visual cues were combined it could lead to an increased user preference and possibly performance, especially in more challenging listening situations (Bentler et al., 2008).

The outcome measures of the study did not indicate user preference or improvement in performance with digital noise reduction turned on (Bentler et al., 2008). There was an improved benefit from adding visual cues of about 4-6 dB, but this benefit was not a result of noise reduction ON (Bentler et al., 2008). The ratings provided by the participants indicated that for ease of listening, noise reduction turned on rated much better than noise reduction turned off for each onset time tested. For listening comfort the
four-second-onset time was rated much poorer than the eight second of noise reduction off condition, and for sound quality there was no difference between noise reduction turned on or turned off (Bentler et al., 2008).

Mueller, Webber & Hornsby examined the effects of digital noise reduction on the acceptance of background noise in 2006. They too cited the work of Ricketts & Hornsby in 2005 noting that participants indicated a significant preference for digital noise reduction ON while listening to speech in noise, and this preference was present for both omnidirectional and directional microphone configurations (Mueller, Webber & Hornsby, 2006). Interestingly, there was no noted improvement in intelligibility tasks in the noise reduction ON condition, indicating that the inclination towards noise reduction ON was based on perceptual factors other than speech intelligibility (Mueller, Webber & Hornsby, 2006).

In the study conducted by Mueller, Webber & Hornsby the acceptable noise level test (ANLT) was used to assess the effectiveness of the digital noise reduction algorithms. The acceptable noise level (ANL) is essentially a SNR that an individual could deal with, if necessary, while listening during a given situation (Mueller, Webber & Hornsby, 2006). This means that a high acceptance of background noise would lead to a low ANL (Mueller, Webber & Hornsby, 2006). An ANL of about 10 dB, or lower, has been used in other research experiments as an indication of successful hearing aid use (Mueller, Webber & Hornsby, 2006). The authors decided to use this method because ANLT is used to assess the annoyance of a component of background noise and since digital noise reduction can be used to reduce the annoyance of background noise, it
seemed that the ANLT could be a useful test to examine the effectiveness of digital noise reduction in the laboratory (Mueller, Webber & Hornsby 2006).

The hearing aid they chose to use in this experiment had two different noise reduction algorithms. One is modulation-based and the other is adaptive fast acting noise reduction. The modulation-based algorithm is set up to decrease gain in a channel specific manner when the dominant signal detected in that particular channel is fairly steady state, classifying it as noise (Mueller, Webber & Hornsby, 2006). The strength of the gain reduction is not dependent on the input level of the signal and can be changed through the programming software (Mueller, Webber & Hornsby, 2006). The adaptive fast acting noise reduction algorithm utilizes a time constant filter, which was set to 10 milliseconds (Mueller, Webber & Hornsby, 2006). Within this time frame the filter follows the envelope of the signal in a manner that is independent within each individual channel and uses that to calculate a SNR (Mueller, Webber & Hornsby, 2006). Within this hearing aid, this form of noise reduction operates continuously (unless all adaptive features of the device are disabled), regardless of the modulations within the input (Mueller, Webber & Hornsby, 2006).

The results indicated that the digital noise reduction did facilitate a significant improvement in ANL measurements (Mueller, Webber & Hornsby, 2006). When the noise reduction was turned off, 45.4% of participants met the set criterion (10 dB), whereas with the noise reduction turned on, 83.6% of participants met the minimum criterion or better (Mueller, Webber & Hornsby, 2006). The question then became which of the hearing aids two noise reduction algorithms was responsible for this improvement.
The background noise in this experiment was created with steady state and stationary components and the noise was set to be on continuously, there were gaps between the sentences, and most ANL testing was completed with SNRs of +5 dB or higher (Mueller, Webber & Hornsby, 2006). With this knowledge about the design of the background noise and the design of the study, it is most likely that the adaptive fast acting noise reduction scheme was responsible for the improvement (Mueller, Webber & Hornsby, 2006). Unfortunately the two noise reduction algorithms could not be uncoupled, so it cannot be said with complete certainty which program was responsible for the improvements in ANL (Mueller, Webber & Hornsby, 2006). However, even though ANL improvements exceeded 10 dB in some cases when noise reduction was ON, it did not indicate any improvement in speech intelligibility (Mueller, Webber & Hornsby, 2006). While the noise reduction would have reduced the noise present in the gaps between words and syllables of sentences, and would have created the perception that the noise was reduced, the SNR of the speech and noise did not actually change (Mueller, Webber & Hornsby, 2006).

Unfortunately, that is about the extent of research that has been conducted to date examining the effectiveness of noise reduction algorithms. The focus recently in the realm of hearing aids has been on the differences between premium and mid-level technology. Another situation where in theory the additional features should provide great benefit, but no evidence has been collected or found to support these claims. Fortunately Cox, Johnson & Xu have conducted two experiments, including a two part experiment, which evaluate some currently available premium level technology to
determine if in fact there is a benefit from this increase in technology, and consequently price tag as well.

Their first experiment examining the difference between basic and premium level technology was conducted in 2014. They evaluated 25 adults with mild to moderate adult onset sensorineural hearing loss in their ability to successfully identify words in the presence of background noise (Cox, Johnson & Xu, 2014). Participant’s speech understanding was tested in a soft, average and loud noise environment (Cox, Johnson & Xu, 2014). They also included questionnaires and patient diaries to determine the effectiveness of the devices (Cox, Johnson & Xu, 2014). Their participant population included both new hearing aid and experiences amplification users (Cox, Johnson & Xu, 2014). They used devices from two major manufacturers and included each company’s basic and premium level technology.

For the soft, average and loud listening environments there was a significant difference in the unaided v. aided scores during the evaluation (Cox, Johnson & Xu, 2014). However, there was no difference in the performance of the participants when wearing basic level in comparison to premium level technology (Cox, Johnson & Xu, 2014). The questionnaires reported a significant improvement in unaided v. aided listening, but their perceived amount of success in communicating during their daily lives was no different for basic or premium level technology (Cox, Johnson & Xu, 2014). Quality of life changes were assessed based on the patient diaries and 96% of patients indicated that their quality of life was ‘at least a little bit better’ with amplification, however the mean rating amongst patients for their experience with amplification was closest to the rating ‘a good deal better’ (Cox, Johnson & Xu, 2014). Again, there was no
difference between the ratings for basic level technology when compared to premium level technology (Cox, Johnson & Xu, 2014).

The first stage of their second round of research focuses on the patients’ perspective. Most participants indicated that their quality of life was at least “moderately better” with the hearing aid in comparison with no amplification (Cox, Johnson & Xu, 2016). There was not a clear difference in the reported quality of life changes across the four hearing aids (two premium and two basic level hearing aids). The mean score was 4.93 (Brand A Basic), 4.62 (Brand B Basic), 4.87 (Brand A Premium) and 4.56 (Brand B premium) (Cox, Johnson & Xu, 2016). This indicates that both technology levels, basic and premium, provided an improvement in quality of life but there was no difference in the improvement provided between the two technology levels (Cox, Johnson & Xu, 2016).

The results found that 96% of the responses for the four different hearing aid models indicated the instruments improved quality of life in comparison to no amplification, but there was no evidence that premium level technology provided more quality of life improvement than basic instruments (Cox, Johnson & Xu, 2016). For each of the four hearing aid models, participants reported relatively high agreement, which is indicative of effectiveness for all models tested (Cox, Johnson & Xu, 2016). The data did not however provide and evidence that the premium level technology was any better then the basic hearing aids at solving issues with speech clarity and noise discomfort, which are frequently faced by hearing aid users (Cox, Johnson & Xu, 2016).

Patient preference reports indicated equally divided preferences between the premium and basic level instruments (Cox, Johnson & Xu, 2016). There was a trend
observed in the results that indicated the second pair of devices was rated to be the primary preference over the first, regardless of technology (Cox, Johnson & Xu, 2016). This was the case even though both technology level and brand were variables that were counterbalanced (Cox, Johnson & Xu, 2016). Previous experience with hearing aids was not a controlled variable in the study, which allowed some comparison to be made between new and previous HA users (Cox, Johnson & Xu, 2016). Neither group indicated a significant difference in quality of life changes between premium and basic level technology (Cox, Johnson & Xu, 2016).

There was also no significant difference between the groups in terms of preference regarding technology level (Cox, Johnson & Xu, 2016). It is not surprising that if a patient is paying thousands of dollars for premium level technology and the added features that entails, they would expect that device to perform better than an instrument with less sophisticated technology (Cox, Johnson & Xu, 2016).

As a whole, participants did not prefer the premium level instruments over the basic technology (Cox, Johnson & Xu, 2016). There was an identical pattern of statistical results when the premium and basic level hearing aids from brand A and brand B were compared separately (Cox, Johnson & Xu, 2016). There was no difference between the two technology levels in terms of the efficiency on users daily life (Cox, Johnson & Xu, 2016). Data from the two major hearing aid manufacturers used in the study were evaluated from the point of view of standard hearing aid users and what their daily lives entailed (Cox, Johnson & Xu, 2016). It appears that the considerably higher dollar amount tied to deemed premium level technology did not result in a realistic increase in the effectiveness of the device in comparison to basic level technology (Cox, Johnson &
Xu, 2016). These findings should result in more cost-conscious and effective hearing aid recommendations and improved access to successful, more affordable, hearing health care for current clinicians (Cox, Johnson & Xu, 2016).

The second part of the research recently conducted by Cox, Johnson & Xu focused on speech understanding and listening effort. Unaided listening regularly lead to worse scores in comparison to each aided listening condition, across all four instruments (Johnson, Xu & Cox, 2016). Among the four aided conditions, the differences were minimal (Johnson, Xu & Cox, 2016). Speech intelligibility was greatly impacted by whether the participant was aided or not, in the soft, average and loud environments (Johnson, Xu & Cox, 2016). There was no difference between premium level and basic level hearing aids in terms of speech intelligibility (Johnson, Xu & Cox, 2016). Unaided listening regularly lead to greater listening effort in comparison to each aided listening condition, across all four instruments, for the soft and average listening situations but not for the loud (Johnson, Xu & Cox, 2016). The use of brand B’s premium level hearing resulted in less listening effort in comparison to the basic level instrument in the loud condition (Johnson, Xu & Cox, 2016). Unaided listening regularly led to less success in comparison to each aided listening condition, across all four instruments (Johnson, Xu & Cox, 2016). Among the four aided conditions, the differences were minimal (Johnson, Xu & Cox, 2016). This suggests that amplification alone greatly increases the perceived occurrence of success in terms of speech intelligibility (Johnson, Xu & Cox, 2016).

Listening effort was reported to improve for both brand A and B for both premium and basic level technology (Johnson, Xu & Cox, 2016). Users perceived aided speech intelligibility benefit in the real world was not significantly influenced by
technology level (Johnson, Xu & Cox, 2016). Users also perceived listening effort in the real world was not significantly influenced by technology level (Johnson, Xu & Cox, 2016). The findings of this study are consistent with prior research that was conducted and found that speech intelligibility and listening effort are improved with amplification (Johnson, Xu & Cox, 2016). This improvement was noted in the laboratory along with in everyday life situations (Johnson, Xu & Cox, 2016). For both brands of hearing aids, for both technology levels, no difference was found in either the laboratory or everyday situations in terms of speech intelligibility or listening effort outcomes (Johnson, Xu & Cox, 2016). Data from participant diaries indicated that the technological advancements that are incorporated into premium level technology were not noticeable or perceived to be of greater value than basic level technology in regards to communicating on a daily basis (Johnson, Xu & Cox, 2016).

This research is necessary for a variety of reasons as indicated by previously completed research evaluating noise reduction algorithms along with premium v. basic level technology. The authors of the current study are not the only ones who feel this way; similar feelings have been expressed in several other publications. Bentler wrote in the 2005 publication of her research examining the effectiveness of directional microphones and noise reduction schemes in hearing aids that she couldn’t find enough research to truly prove the effectiveness of noise reduction schemes. She called for more research to be done to prove clinical effectiveness (Bentler, 2005). Mueller, Webber & Hornsby expressed frustration about the fact that there has been a great deal of written information discussing the potential benefits of DNR regarding speech comprehension and listening comfort, but there is very little published evidence that actually supports
these claims (Mueller, Webber & Hornsby, 2006). This was written in their 2006 paper examining the effects of digital noise reduction on the acceptance of background noise.

However, the greatest call to the field for more clinical research evaluating the claims made by manufacturers was made by Cox, Johnson & Xu in their two part publication that evaluated the impact of hearing aid technology on outcomes in daily life in 2016. They stated in their research that a recurrent theme is the opinion that hearing aids do not perform at a level to justify the price tag associated with them (Cox, Johnson & Xu, 2016). Research indicates that patients often conduct a cost-benefit analysis to aid in deciding the true value of hearing aids (Cox, Johnson & Xu, 2016). These cost-benefit analyses have shown that instruments that deliver more benefit for a particular cost or the same benefit at a smaller price point are perceived to offer a greater value (Cox, Johnson & Xu, 2016). This can be taken to mean that hearing aids that provide more value per unit of cost to the patient are more likely to be accepted (Cox, Johnson & Xu, 2016).

Although cost is not the only factor that determines whether or not a hearing aid will be considered valuable to accepted but a patient, it is a major contributor to that decision (Cox, Johnson & Xu, 2016). Interestingly, it is known that perceived cost-benefit outcomes are important to patients in determining the value of hearing aids; very little research has been conducted in this area (Cox, Johnson & Xu, 2016).

Every manufacturer today presents their instruments in “families” which include three or four models, each with progressively more sophisticated technology levels (Cox, Johnson & Xu, 2016). As the technology levels increase, so does the associated price tag with that instrument (Cox, Johnson & Xu, 2016). The hearing aids that are available currently have digital signal processing features that are created to increase outcomes in a
variety of listening situations (Cox, Johnson & Xu, 2016). One of these is digital noise reduction, which was designed to decrease the gain of unintended noises (Cox, Johnson & Xu, 2016). The lower level technology within a “family” still included all of the features currently available as part of digital signal processing but the premium levels are said to house more complex, automatic, and adaptive versions of these same processing features along with some features that are not even offered in the more basic technology levels (Cox, Johnson & Xu, 2016).

With this in mind, it would seem obvious to assume that the more complex, adaptive, and automatic signal processing features within a hearing aid are the more benefit the user would gain throughout their daily life (Cox, Johnson & Xu, 2016). If this is the case, the cost-benefit analysis would at least stay constant, with the potential for an increase, for these premium level devices (Cox, Johnson & Xu, 2016). While this all sounds nice and logical based on the theory behind premium level technology, unfortunately increased real life benefit from using this technology has not been found in independent research thus far (Cox, Johnson & Xu, 2016). The self reported needs of some patients may suggest a potential benefit from premium level technology, while others may benefit in terms of experience and cost from more basic level technology (Cox, Johnson & Xu, 2016).

It has been suggested that this higher level technology provides greater access to speech cues given the advanced signal processing features and in doing so would also reduce the effort required to listen in challenging environments, which would consequently result in less fatigue; unfortunately this theory has not yet been proven (Johnson, Xu & Cox, 2016). Based on the foundation that premium level technology has
been created on, it is not surprising that it is assumed premium level technology would further decrease listening effort in comparison to basic level technology (Johnson, Xu & Cox, 2016). Thus far, the research that has been conducted to evaluate this theory has not found any better or improved listening effort with premium level technology in comparison with basic level hearing aids (Johnson, Xu & Cox, 2016).

To date there is little independent research that has explored if more advanced signal processing actually provides more advanced outcomes in specific listening environments (Johnson, Xu & Cox, 2016). In order for practitioners to make evidence grounded recommendations independent research needs to be conducted to evaluate premium and basic level technology in not only laboratory but also real world situations (Johnson, Xu & Cox, 2016). The focus on this research needs to be improvement in speech intelligibility and listening effort (Johnson, Xu & Cox, 2016). Hearing aids that are identified as premium level technology, and therefore more advanced, are associated with a much higher price tag than basic level technology (Johnson, Xu & Cox, 2016). With this higher price tag it is assumed these instruments will provide greater improvements in speech understanding and listening effort (Johnson, Xu & Cox, 2016). However, research did not find this to be the case (Johnson, Xu & Cox, 2016). Instead it was found that amplification is significantly better than no amplification in these areas, but in all the facets that data was collected and analyzed there was no difference between premium and basic level technology (Johnson, Xu & Cox, 2016).

Unfortunately, clinicians do not have any guidelines grounded in scientific evidence to help them determine which patients fit into which category (Cox, Johnson & Xu, 2016).
Instead they have to rely on claims made by manufacturers, which are frequently unverified, to decide which technology level to recommend to patients (Cox, Johnson & Xu, 2016). Often times patients will ask about the difference in technology levels and clinicians are forced to ramble off the claims manufacturers have made or the differences in features between the two, but that rarely translates to differences the patients will perceive in their daily life (Cox, Johnson & Xu, 2016). This is not an acceptable manner to determine which technology level is recommended to an individual (Cox, Johnson & Xu, 2016). It is imperative that practitioners have access to real world improvements their patients will experience with each technology levels and that these improvements are based on scientific evidence in order to make sound recommendations to patients (Cox, Johnson & Xu, 2016).

There have been many studies that examine if there is an improvement in speech understanding and perception with noise reduction ON. The results have been marginal at best, most indicating a perceptual improvement when digital noise reduction is enabled according to patient reports, but performance on speech related tasks does not indicate any improvement with noise reduction ON in comparison to OFF. However, there haven’t been any studies that examine if the digital noise reduction algorithms objectively do what they are supposed to do, which is why this study is necessary. The findings of the current study will contribute to the scare independent research that is currently available to aid clinicians in making recommendations for their patients regarding which technology level best suits their needs, recommendations that need to be based on sound scientific evidence.
References:


