

**THE EFFECT OF HIGH FREQUENCY AMPLIFICATION
ON SUBJECTIVE AND OBJECTIVE
BENEFIT WITH DIGITAL HEARING INSTRUMENTS**

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ABSTRACT

The purpose of the present study was to determine whether amplifying beyond 3 kHz was beneficial to the user, whether the benefit was dependent on degree of loss, and whether subjective data reflected the benefit. Seventeen hearing impaired subjects were binaurally fitted with digital hearing instruments. Qualified subjects were divided into two groups, A and B. Group A had a pure tone average (3,4, and 6 kHz), of 55 dBHL or better. Group B had a pure tone average (3,4, and 6 kHz) greater than 55 dBHL but not exceeding 75 dBHL. Each subject was fit with two conditions (upward frequency response of 3 kHz and 6 kHz) throughout the study. Probe microphone measurements were obtained at the plane of the tympanic membrane using a swept pure tone of 60 dB SPL to verify appropriate fit of the hearing instruments. Listener performance in quiet was evaluated via the Connected Speech Test (CST), listener performance in noise was evaluated via the CST and the Hearing in Noise Test, and listener preference was evaluated via the Abbreviated Profile of Hearing Aid Benefit and an exit questionnaire. Results of the probe microphone measures indicated that the mean output levels for each condition were significantly different. Results indicated that increasing the bandwidth did not significantly improve benefit in quiet for either group but did significantly improve benefit in noise for each group. However, the amount of benefit was similar for each bandwidth suggesting that the amount of benefit is not dependent on degree of loss. Subjective data suggested that amplifying beyond 3 kHz did not increase subjective benefit according to the APHAB. However, results from the exit questionnaire suggest that the 6 kHz condition was preferred by the majority of the subjects overall, both in quiet and in noise.

CHAPTER I

INTRODUCTION

Conventional analog hearing instruments typically amplify up to 3000 Hz whereas digital hearing instruments are capable of amplifying up to 5000-6000 Hz. What remains unclear is whether amplifying regions up to 5000-6000 Hz is beneficial to the user. According to the articulation index (AI) theory, increasing the frequency response beyond 3 kHz would increase the audibility of the speech signal from .76 to 1.0. Providing increased audibility in the high frequency regions may result in increased speech intelligibility. Most research suggests that AI values more accurately predict speech intelligibility for listeners with mild-to-moderate hearing loss than for listeners with greater degrees of hearing loss or precipitously sloping audiometric configurations. Therefore, the next logical question is whether the benefit of amplification up to 5000-6000 Hz is dependent on degree of loss or type of configuration.

Some research suggests that the benefit of providing high frequency amplification depends on degree of loss and type of configuration. Results indicate that benefit of amplification beyond 4 kHz diminishes once the hearing loss has exceeded 55 dB HL for listeners with a sloping configuration but not a flat configuration.

In contrast, some research has demonstrated that providing an extended frequency response is beneficial to the listener, especially in noisy conditions, regardless of degree of loss or type of configuration. However, providing the extended frequency may be detrimental to sound quality. Furthermore, research suggests that listeners with dead cochlear regions are unable to make use of high frequency information.

To date, there is a lack of indisputable research or literature that either supports amplifying high frequency regions or opposed to amplifying high frequency regions. As the

trend in fitting hearing instruments shifts toward digital products, whether or not amplifying high frequency regions is beneficial becomes more relevant.

CHAPTER II

REVIEW OF LITERATURE

INSTRUMENTATION

Analog Hearing Instrument

Traditional analog hearing instruments consist of a microphone, a preamplifier, a means processor by way of a tone control or automatic gain control, an amplifier, and a receiver.

Acoustic signals are converted to electrical input signals by the microphone and then sent to the preamplifier. The frequency response of the amplified electrical input signals are shaped by the means processor. The signals are again amplified and transduced back to acoustic signals through the receiver (Lopez, 2001).

Digital Hearing Instrument

Digital hearing instruments consist of a microphone, preamplifier, analog-to-digital converter, digital signal processor, digital-to-analog converter, amplifier, and a receiver. Analog signals are transduced by the microphone into an electrical input signal. The electrical input signals are amplified by the preamplifier and then digitized in a numbered sequence by the digital-to-analog converter. Following the digitization, the digital signals are spectrally shaped according to specified algorithms within the digital signal processor. The digital signals are then converted into electrical signals by the digital-to-analog converter. The signals are again amplified and transduced into acoustic output signals by the receiver (Lybarger, S.F. and Lybarger, E.H. 2000). Digital signal processing (DSP) allows for a more specific representation of the acoustic signal as compared to an analog processor.

Features Available with Digital Processing

The advent of the DSP resulted in several modifications in hearing instrument technology. Using an integrated computer chip permitted complex signal processing, such as

DSP, to occur within a compact space. This in turn allowed for a smaller hearing instrument requiring less power consumption. Internal noise is also reduced. Internal noise is dependent on the complexity of the incoming signals. Internal noise created by analog instruments is reduced in DSP instruments due to the greater number of bits allowed in the system (Holube, I. & Velde, T.M., 2000).

Traditionally, digital hearing instruments have offered features not available in analog instruments such as feedback management, noise reduction, and speech enhancement (Ricketts, T. 2001). Although, there is no indisputable evidence or literature supporting that digital hearing instruments provide significantly greater benefit than traditional analog instruments, DSP instruments do appear to provide some advantages in terms of hearing instrument flexibility. Increased flexibility is attributed to the greater number of channels and lower knee points available in DSP products; thereby allowing for better control of compression across frequencies (Ricketts, T. 2001; Arlinger, S. 1997). The improved flexibility afforded by DSP instruments may thereby enable the dispenser to better shape frequency responses during fittings. DSP instruments also provide the capability of producing a broader frequency response than analog instruments. Analog instruments typically amplify up to 3000 Hz, whereas DSP instruments are capable of amplifying up to 5000-6000 Hz. Therefore, DSP instruments provide a broader frequency response and potentially increase audibility of high frequency speech cues not amplified by analog devices.

ARTICULATION INDEX PREDICTIONS

Although DSP instruments are capable of providing a broader frequency response than analog instruments, what remains unclear is if providing a broader frequency response is beneficial to the instrument user. The Articulation Index (AI) is a tool that determines the

audibility of the speech signal. AI calculations are based on the percent of audible speech bands and the regions the speech bands encompass. There are many methods or AI calculations, however, the calculations differ mainly in number of bands, weightings assigned to each band, and the type of speech stimuli used during calculations (Staab, W.J., 2000). One such calculation is the “Count-the-Dots” method by Mueller and Killion (1990).

The “Count-the-Dots” method weights different frequencies according to their importance for speech understanding. 100 dots are distributed over a 30 dB range across the speech frequencies. All dots falling above the listener’s threshold are deemed audible. The total number of dots counted is then divided by 100 and the resulting calculation provides the listener’s predicted AI.

According to the “Count-the-Dots” method, there are exactly 24 dots above 3 kHz. Therefore, the utilization of a conventional hearing instrument would result in a maximum AI of .76. However, extending the frequency response from 3 kHz to 6 kHz would increase the AI from .76 to 1.0. Stated differently, the use of DSP instruments may increase audibility of the speech signal in the frequency regions where several speech cues are located. Consequently, the increased audibility in the high frequency regions may result in increased speech intelligibility.

As previously mentioned, the AI attempts to predict speech intelligibility based upon the available speech audibility rather than using objective measurements. Stated differently, the AI quantifies the total audibility of the speech signal available to the listener in order to predict speech intelligibility (Pavlovic, C.V 1988). Using AI to predict speech intelligibility assumes that speech intelligibility increases as the AI increases. Research has demonstrated that the AI is a good indicator of speech recognition for normal hearing listeners and those with mild-to-moderate sensorineural hearing loss (Pavlovic, C.V. 1984). However, the AI may be a poor

indicator of speech intelligibility for listeners with moderate-to-severe sensorineural hearing loss (Ching et al, 1998; Pavlovic, C.V. 1984; Studebacker et al., 1994). Furthermore, Rankovic (1991) demonstrated that maximizing the AI for listeners with a steeply sloping audiometric configuration resulted in poor performance on speech recognition tests. These results suggest that AI values more accurately predict speech intelligibility for listeners with mild-to-moderate hearing loss than for listeners with greater degrees of hearing loss or precipitously sloping audiometric configurations.

In summary, the AI predicts an increase from 76% to 100% in speech intelligibility by extending the frequency response from 3 kHz to 6 kHz. Current research suggests that the increase in speech intelligibility predicted by the AI is dependent on degree of loss and configuration of loss. Research suggests that the AI accurately predicts increased speech intelligibility for mild to moderate hearing loss and for listeners with flat to slightly sloping configurations. Therefore, DSP hearing instruments, with an extended frequency response from 3 kHz to 6 kHz, should increase speech intelligibility for listeners with a mild to moderate hearing loss and a relatively flat to slightly sloping configuration.

SUPPORT AGAINST HIGH FREQUENCY AMPLIFICATION

There are a variety of studies that make different claims about the effect of high frequency amplification. Byrne (1986) reported that listeners with sloping high frequency hearing loss judged the amplification providing the most extended high frequency emphasis to be the poorest in intelligibility. Most of the hearing instruments used in the study failed to amplify beyond 3 kHz. (Need to get the study from the library in order to expand)

Hogan and Turner (1998) evaluated the effects of hearing loss configuration and severity as well as the frequency bandwidth that maximized speech recognition scores. Speech

recognition was tested at various band pass settings for 5 normal hearing listeners and 9 hearing impaired listeners with varying degrees of high frequency hearing loss. The test stimuli were presented through a Sennheiser HD 25-SP earphone with a supra-aural cushion. Results for the normal hearing listeners demonstrated an increase in speech recognition scores as audibility increased. Results for the listeners with mild high frequency loss were similar to the normal hearing listeners, whereas, results for listeners with moderate high frequency loss were poorer than those obtained from either the normal hearing listeners or mildly impaired listeners. Generally, the results indicated that benefits of amplification were diminished once the degree of loss exceeded 55 dB HL. Benefits of amplification were significantly more decreased when the degree of loss exceeded 55 dB HL and the hearing loss fell in regions beyond 4 kHz as compared to when the hearing loss fell in regions below 4 kHz.

Likewise, Turner and Cummings (1999) evaluated the benefit of providing audible speech information to listeners with a high frequency hearing loss. Speech recognition was tested over a wide range of presentation levels for 10 listeners with various degrees and configurations of sensorineural hearing loss. The test stimuli were presented through Sennheiser HD 25-SP headphones. Turner reported that for listeners with a sloping loss, amplifying frequencies beyond 3 kHz resulted in little to no improvement in speech recognition scores when hearing loss exceeded 55 dB HL. For flat configurations, however, amplifying frequencies beyond 3 kHz resulted in an increase in speech recognition when hearing loss exceeded 55 dB HL. These results suggest that benefit obtained from amplifying beyond 3 kHz depends on the configuration of loss.

Sullivan et al. (1992) speculated the increase in speech recognition for listeners with flat configurations was contributed to greater gain in the high and mid-frequencies rather than simply

amplification beyond 3 kHz. Without amplification, listeners with sloping losses were already receiving the maximum mid-frequency speech cues plus some high frequency speech cues. With amplification, listeners received only additional high frequency speech cues which resulted in little to no improvement in speech recognition scores. Without amplification, listeners with flat configurations received some mid-frequency and high frequency speech cues. With amplification, listeners with flat configurations received additional mid-frequency and high frequency speech cues which resulted in a significant improvement in speech recognition scores. Stated differently, with amplification, listeners with sloping losses were receiving high frequency speech cues whereas listeners with flat losses were receiving speech cues in the high frequencies as well as the low to mid-frequencies. Therefore, Sullivan et al. concluded that studies suggesting speech recognition scores improved due to high frequency amplification are questionable.

In a follow-up study, Turner and Brus (2001) evaluated the effects of providing audible speech information to the low and mid-frequency regions for listeners with various degrees of sensorineural hearing loss. Nonsense syllable recognition was tested on 5 normal hearing and 13 hearing impaired listeners with a range of hearing loss in the low and mid-frequency regions. The test stimuli were presented through Sennheiser HD 25-SP circumaural headphones. Turner and Brus reported that for frequencies below 2800 Hz, amplification provided positive benefit for recognition scores regardless of degree of loss rather than the 55 dB HL suggested by Hogan and Turner. These results suggest that speech recognition scores will improve without amplifying beyond 3000 Hz for listeners with any configurations.

In summary, research suggests that the benefit of providing high frequency amplification depends on degree of loss and type of configuration. Results indicate that benefit of

amplification beyond 4 kHz diminishes once the hearing loss has exceeded 55 dB HL for listeners with a sloping configuration but not a flat configuration.

SUPPORT FOR HIGH FREQUENCY AMPLIFICATION

There are some studies that provide support for high frequency amplification. Sullivan et al. (1992) evaluated the effects of various cutoff frequencies on objective and subjective performance of listeners with steeply sloping, high frequency hearing loss. Nonsense syllable recognition and subjective ratings of speech intelligibility and speech quality were obtained from 17 males with bilateral symmetrical high frequency sensorineural hearing loss. The test stimuli were presented through a headphone transducer. Sullivan et al. found that syllable recognition increased when additional high frequency information beyond 2 kHz was available; however, the additional amplification was reported to be detrimental to sound quality. Stated differently, performance improved but at the expense of sound quality.

Vickers et al (2001) evaluated the effect of high frequency amplification on speech perception for hearing impaired listeners with and without dead cochlear regions in the high frequencies. Speech performance was measured using nonsense syllables low-pass filtered at various cutoff frequencies for 10 listeners. The test stimuli were presented through HD580 earphones. Seven listeners had dead regions in the high frequencies and three listeners were without dead regions in the high frequencies. Results suggested that listeners without dead cochlear regions were able to make use of high frequency information towards speech intelligibility; however, continued increases in amplification resulted in decreased performance. Vickers et al. stated that determining where dead regions occur can be used as an alternative to AI calculations when determining amplification needs. It should be noted that the subjects with dead regions had more high frequency hearing loss than those without dead regions. Therefore,

the improved performance by subjects without dead regions may have been attributed to degree of hearing loss rather than the absence of cochlear dead regions (Rankovic, 2002).

Schwartz et al. (1979) examined the effect of an experimental high-pass hearing instrument versus a conventional high frequency emphasis hearing instrument on word recognition and consonant discrimination in both quiet and noise conditions. Ten male listeners with bilaterally symmetrical high frequency sensorineural hearing loss past 1 kHz were tested in quiet and noise under 3 conditions: unaided, conventional high frequency emphasis hearing instrument (own aid) and wearing the experimental high-pass instrument. Results suggested similar benefit for both hearing instruments in the quiet conditions. However, in the noise conditions, results indicated a greater increase in recognition scores with the experimental high-pass instrument. The experimental high-pass instrument's frequency response amplified up to 5200 Hz whereas most of the conventional high emphasis hearing instruments amplified up to 3000-4000 Hz. The listeners reported that the high-pass hearing instrument was superior, quieter and improved clarity of speech.

Results judging quality and superiority should be interpreted with caution mainly because testing was conducted under ideal laboratory conditions using the listener's old hearing instruments versus the new hearing instruments. Also, many dispensers are hesitant to rely on results obtained from speech scores in a simulated environment or ratings of sound quality unless listeners have a period of time to adjust to the new aided signals (Berger, 1992).

In summary, research has demonstrated that providing an extended frequency response is beneficial to the listener, especially in noisy conditions, regardless of degree of loss or type of configuration. However, providing the extended frequency may be detrimental to sound quality. Furthermore, research suggests that listeners without dead cochlear regions are able to make use

of high frequency information. It should be noted that the amount of benefit may be dependent on the degree of loss rather than the absence of cochlear dead regions.

CHAPTER III

RATIONAL

Conventional hearing instruments typically amplify up to 3000 Hz whereas digital hearing instruments are capable of amplifying up to 5000-6000 Hz. What remains unclear is whether amplifying regions up to 5000-6000 Hz is beneficial to the user. According to the AI, increasing the frequency response beyond 3 kHz would increase the audibility of the speech signal from .76 to 1.0. Providing increased audibility in the high frequency regions may result in increased speech intelligibility. However, most of the research suggests that AI values more accurately predict speech intelligibility for listeners with mild-to-moderate hearing loss than for listeners with greater degrees of hearing loss or precipitously sloping audiometric configurations. Therefore, the next logical question is whether the benefit of amplification up to 5000-6000 Hz is dependent on degree of loss or type of configuration.

Some research suggests that the benefit of providing high frequency amplification depends on degree of loss and type of configuration. Results indicate that benefit of amplification beyond 4 kHz diminishes once the hearing loss has exceeded 55 dB HL for listeners with a sloping configuration but not a flat configuration.

In contrast, some research has demonstrated that providing an extended frequency response is beneficial to the listener, especially in noisy conditions, regardless of degree of loss or type of configuration. However, providing the extended frequency may be detrimental to sound quality. Furthermore, research suggests that listeners without dead cochlear regions are able to make use of high frequency information. It should be noted that the amount of benefit may be dependent on the degree of loss rather than the absence of cochlear dead regions.

To date, there is a lack of indisputable research or literature that either supports amplifying high frequency regions or opposed to amplifying high frequency regions. Also there is a lack of research, objective or subjective, performed outside of the laboratory with actual hearing instruments. Therefore, the purpose of this study is to address the following questions:

- 1) is amplifying up to 5000-6000 Hz beneficial to the user?
- 2) Is benefit of amplifying up to 5000-6000 Hz dependent on degree of loss?
- 3) Does subjective data reflect benefit or lack of benefit due to amplification up to 5000-6000 Hz?

CHAPTER IV

METHODOLOGY

SUBJECTS

Seventeen hearing impaired persons participated in this study. Inclusion criteria included a) pure tone air and bone conduction thresholds exceeding 20 dB HL in at least 4 of the six octave interval frequencies from 250 Hz to 8000 Hz (ANSI S3.6-1996), b) pure tone air and bone conduction thresholds not exceeding 75 dB HL from 3000 Hz to 6000 Hz (ANSI S3.6-1996), c) normal tympanograms bilaterally, d) unremarkable otoscopy, and E) no previous hearing instrument experience. Their ages ranged from 18 to 85 years. All qualification and experimental test were conducted in a sound-treated examination room (Industrial Acoustic) with ambient noise levels suitable for testing with ears uncovered (ANSI S3.1-1991).

STIMULI

The Connected Speech Test (CST, The University of Memphis) and the Hearing in Noise Test (HINT, House Ear Institute) served as the stimuli. The CST consisted of 50 passages of 10 subject related English sentences. The HINT consisted of 25 lists of 10 English sentences. All speech stimuli and background noise were produced by a compact disc player and routed through a two-channel diagnostic audiometer (GSI-61) to a loudspeaker located in the sound treated examination room. All speech stimuli were presented at a normal conversational level of 60 dB HL. The output levels of the speech stimuli and background noise were calibrated at the vertex of the listener and were checked periodically throughout the experiment.

HEARING INSTRUMENTS

Prior to experimental testing, the qualified subjects were divided into two groups, A and B. Group A had a pure tone average (3,4, and 6 kHz), of 55 dBHL or better. Group B had a

pure tone average (3,4, and 6 kHz) greater than 55 dBHL but not exceeding 75 DbHL (see Appendix A). Both groups were fit bilaterally with digital Starkey Axent completely-in-the-canal hearing instruments. Half of group A and B hearing instruments were set with an upper frequency response limit of 3 kHz for a period of 6 weeks and then increased to an upper frequency response limit of 6 kHz for 6 weeks. Half of group A and B hearing instruments were set with an upper frequency response limit of 6 kHz for 6 weeks and then decreased to an upper frequency response limit of 3 kHz for 6 weeks. Dividing the groups in this manner attempted to account for any possible acclimatization. The test instruments utilized in this study were identical in appearance and the subjects were unaware of which instrument setting they were fit with at all times.

HEARING INSTRUMENT FITTING

The digital hearing instruments were programmed for each subject using the subject's audiometric information and the desired sensation level fitting strategy. Uncomfortable loudness level (UCL) data were not measured, therefore, predicted UCL values were utilized for all subjects.

Real ear measurements were made on each subject to verify appropriate fit of the hearing instruments using an Audioscan RM500 probe microphone system. Real ear insertion gain measures were obtained using a swept pure tone at 60 dB SPL. The probe microphone system measurements consisted of 65 data points measured in 1/12th octave steps over a frequency range of 200 Hz to 8000 Hz. Data for output levels at the tympanic membrane stored in the Audioscan RM500 were downloaded to a personal computer for subsequent data analysis.

EXPERIMENTAL PROTOCOL

Prior to the hearing instrument fitting, subjects were tested in unaided conditions on both the HINT and the CST tests and completed the “Without My Hearing Aids” section of the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995). The APHAB is a 24-item inventory, scored in four subscales. The subjects rank each statement according to the difficulties experienced in a variety of settings with and without the hearing instruments.

After the initial hearing instrument fitting, subjects were tested in aided conditions on both the HINT and the CST test. After 6 weeks of use, the subjects were retested under the first aided condition using the HINT and the CST test, as well as completing the “With My Hearing Aids” portion of the APHAB. The frequency response characteristic of the hearing instruments was then switched for each group. The subjects were again tested on the HINT and the CST test under the second aided condition. After 6 more weeks of use, the subjects completed two replications of the “With My Hearing Aids” portion of the APHAB comparing the second condition with unaided performance as well as comparing between conditions. The subjects then completed final testing on the HINT and the CST test.

CHAPTER IV

RESULTS

PROBE MICROPHONE MEASURES

Binaural probe microphone measures were obtained at the plane of the tympanic membrane of each subject to verify the response characteristics of each hearing instrument for each condition. Probe microphone measures obtained were also used to determine the relative articulation index (AI) value of each subject for each condition. Hearing instrument responses obtained at the right ear and at the left ear of each subject were averaged across the seventeen subjects to determine the mean response characteristics of the hearing instruments for each bandwidth condition. Similarly, the aided AI values obtained at the right ear and at the left ear of each subject were subtracted from the unaided AI values at the right and left ear of each subject to determine the relative AI score for each ear. Relative AI scores were then averaged across the seventeen subjects for each condition to determine mean relative AI score of each subject for each bandwidth condition (Figure 1).

A two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group. The dependent variable was relative AI score. The within subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed significant main effects for bandwidth [$F(1,15) = 398.568, p < 0.05$] and for group [$F(1,15) = 135.897, p < 0.05$]. No significant effects were evident for the bandwidth by group interaction [$F(1,15) = 18.533, p > 0.05$]. These results indicated that group B received a significantly greater AI increase than group A for each bandwidth condition. These results further indicated that the

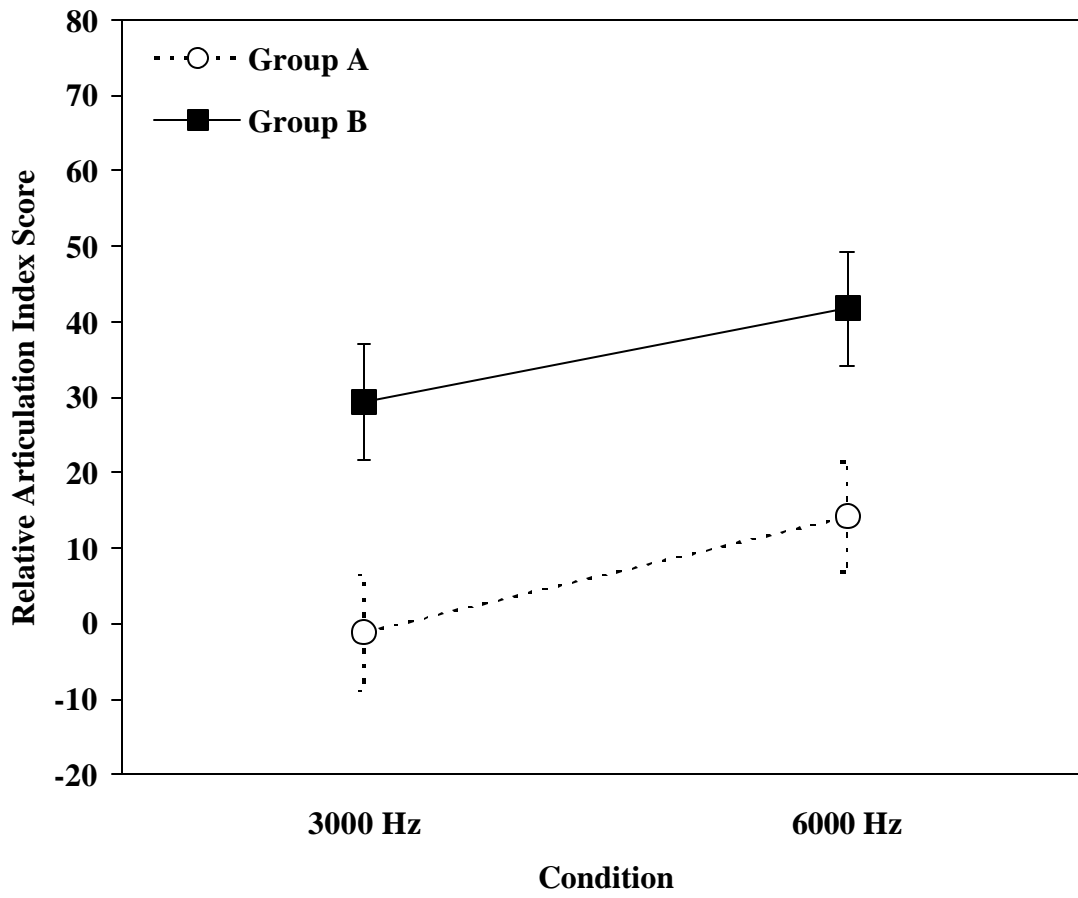


Figure 1: Relative articulation index scores.

aided AI values were significantly greater for the 6 kHz condition than for the 3 kHz condition for each group.

EXPERIMENT I: OBJECTIVE TESTING

One purpose of the present study was to objectively evaluate listener performance in quiet when utilizing the 3 kHz or 6 kHz hearing instrument bandwidth setting. The Connected Speech Test (CST) was conducted at 65 dB SPL for each subject at the beginning and the end of each six-week trial period. Each subject's aided CST scores were averaged together for each bandwidth condition. The unaided CST score was then subtracted from the aided CST score to determine each subject's relative CST score in quiet for each bandwidth condition. Relative CST scores in quiet were then averaged across the seventeen subjects for each bandwidth condition (Figure 2).

A two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group. The dependent variable was relative CST score in quiet. The within-subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed significant main effects for group [$F(1,15) = 8.605, p < 0.05$]. No significant main effects were evident for the bandwidth [$F(1,15) = 0.052, p > 0.05$] or for the bandwidth by group interaction [$F(1,15) = 0.029, p > 0.05$]. These results indicated that group B received a significantly more benefit in quiet than group A for each bandwidth condition. These results further indicated, however, that increasing the hearing instrument bandwidth did not significantly improve benefit in quiet for either group.

Listener performance was also evaluated in noise when utilizing the 3 kHz or 6 kHz hearing instrument bandwidth setting. The Connected Speech Test (CST) and the Hearing in

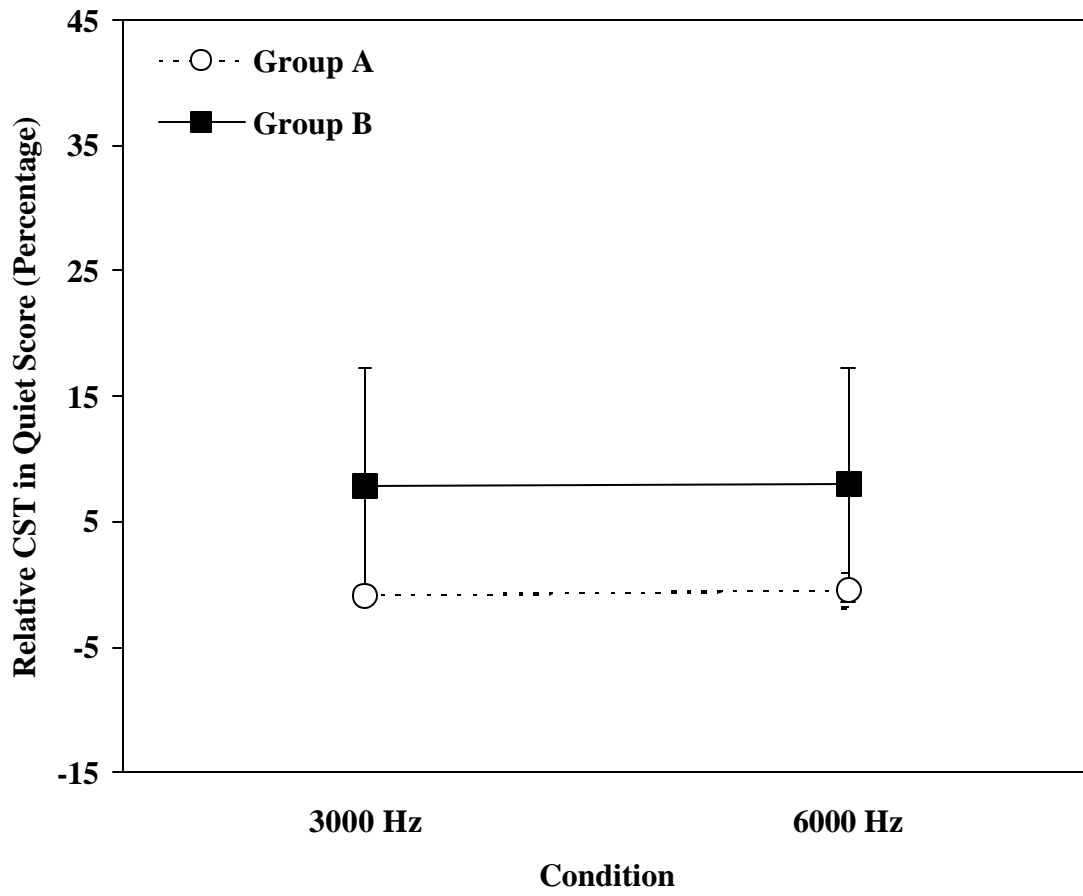


Figure 2: Relative connected speech test scores in quiet for each bandwidth.

Noise Test (HINT) were conducted at the beginning and the end of each six-week trial period for each subject. Each subject's aided CST scores and aided HINT scores were averaged together for each bandwidth condition. The unaided CST and the unaided HINT score was then subtracted from the aided CST and HINT score to determine each subject's relative CST score in noise and relative HINT score for each bandwidth condition. Relative CST scores in noise and relative HINT scores were then averaged across the seventeen subjects for each bandwidth condition (Figures 3 & 4).

A two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group. The dependent variable was relative CST score in noise. The within-subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed significant main effects for bandwidth [$F(1,15) = 7.258, p < 0.05$] and for group [$F(1,15) = 5.109, p < 0.05$]. No significant main effects were evident for the bandwidth by group interaction [$F(1,15) = 3.835, p > 0.05$].

A two-way analysis of variance was also performed on the HINT data. The dependent variable was relative HINT score. The within-subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed significant main effects for bandwidth [$F(1,15) = 4.667, p < 0.05$] and for group [$F(1,15) = 7.221, p < 0.05$]. No significant main effects were evident for the bandwidth by group interaction [$F(1,15) = 0.097, p > 0.05$]. These results indicated that group B received significantly more benefit in noise than group A for each bandwidth condition. These results further indicated that increasing the hearing instrument bandwidth significantly improved benefit in noise for each group.

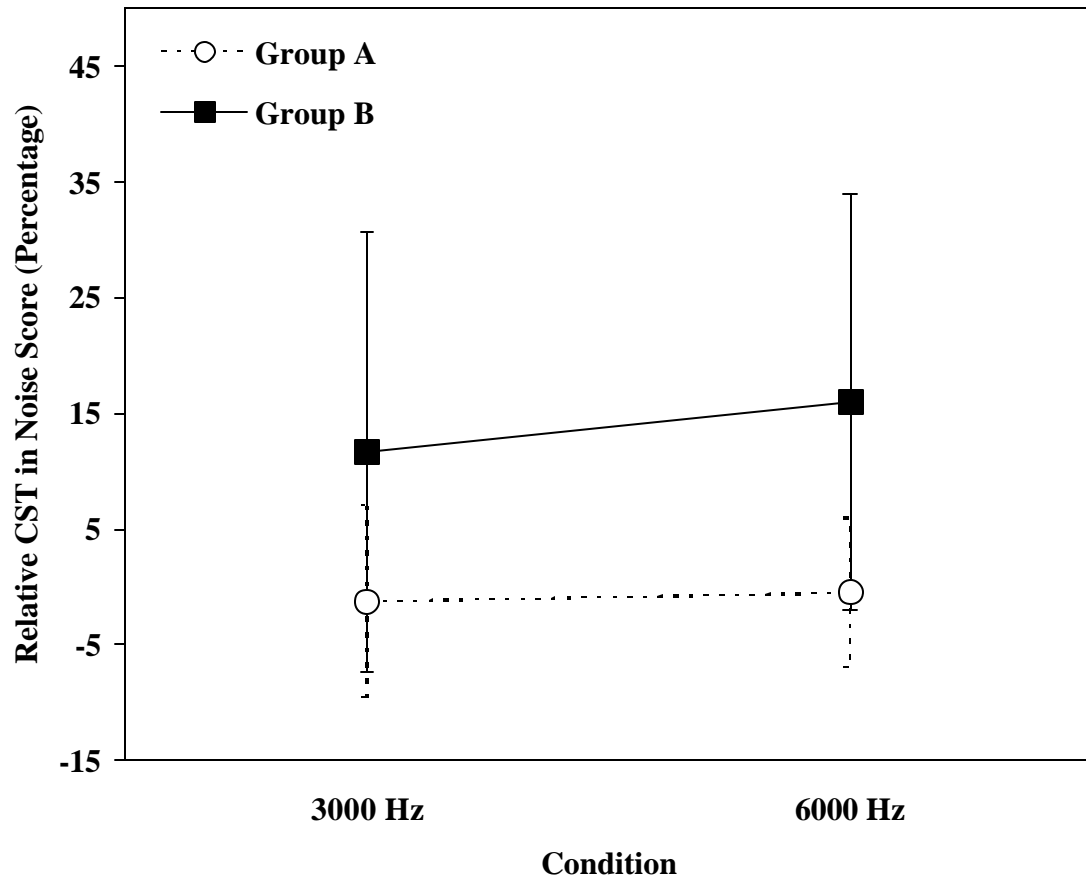


Figure 3. Relative connected speech test scores in noise for each bandwidth

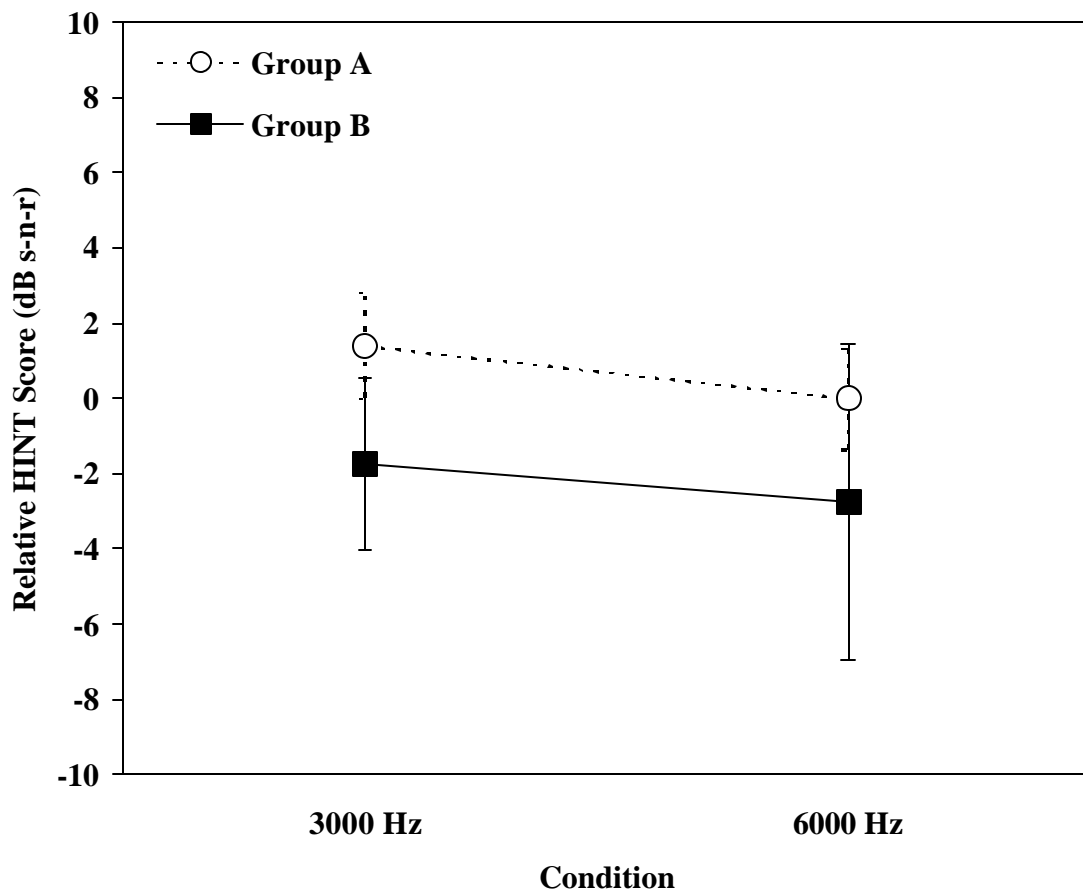


Figure 4: Relative hearing in noise test scores for each bandwidth

EXPERIMENT II: SUBJECTIVE TESTING

Another purpose of the present study was to subjectively evaluate listener performance when utilizing the 3 kHz or 6 kHz hearing instrument bandwidth setting. Each subject was administered the APHAB prior to their initial fitting to determine their unaided scores (percentage of problems) in each APHAB subscale (EC, RV, BN, AV). Each subject also completed the APHAB at the end of the 3 kHz bandwidth trial period and at the end of the 6 kHz bandwidth trial period. Benefit scores were then calculated for each subscale by subtracting the APHAB scores obtained in each aided condition from the APHAB scores obtained in the unaided condition. APHAB benefit scores were then averaged across the seventeen subjects for each bandwidth condition (Figure 5-8).

A two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group on subjective benefit in the ease of communication subscale (EC). The dependent variable was EC benefit score. The within-subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed significant main effects for group [$F(1,15) = 5.762, p < 0.05$]. No significant main effects were evident for the bandwidth [$F(1,15) = 0.933, p > 0.05$] or for the bandwidth by group interaction [$F(1,15) = 1.194, p > 0.05$]. These results indicated that group B reported significantly more benefit in quiet environments than group A for each bandwidth condition. These results further indicated, however, that increasing the hearing instrument bandwidth did not significantly improve reported benefit in quiet for either group.

A two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group on subjective benefit in the reverberation subscale (RV). The

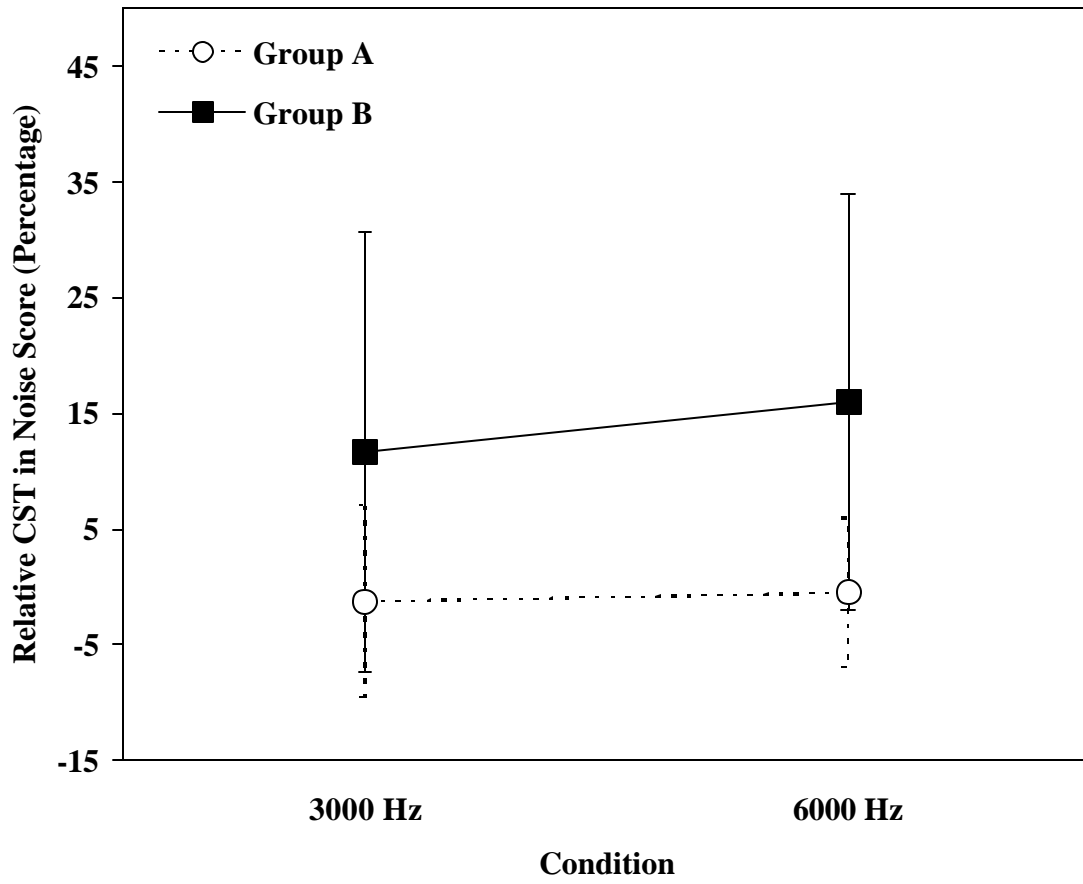


Figure 5: Ease of communication benefit for each bandwidth

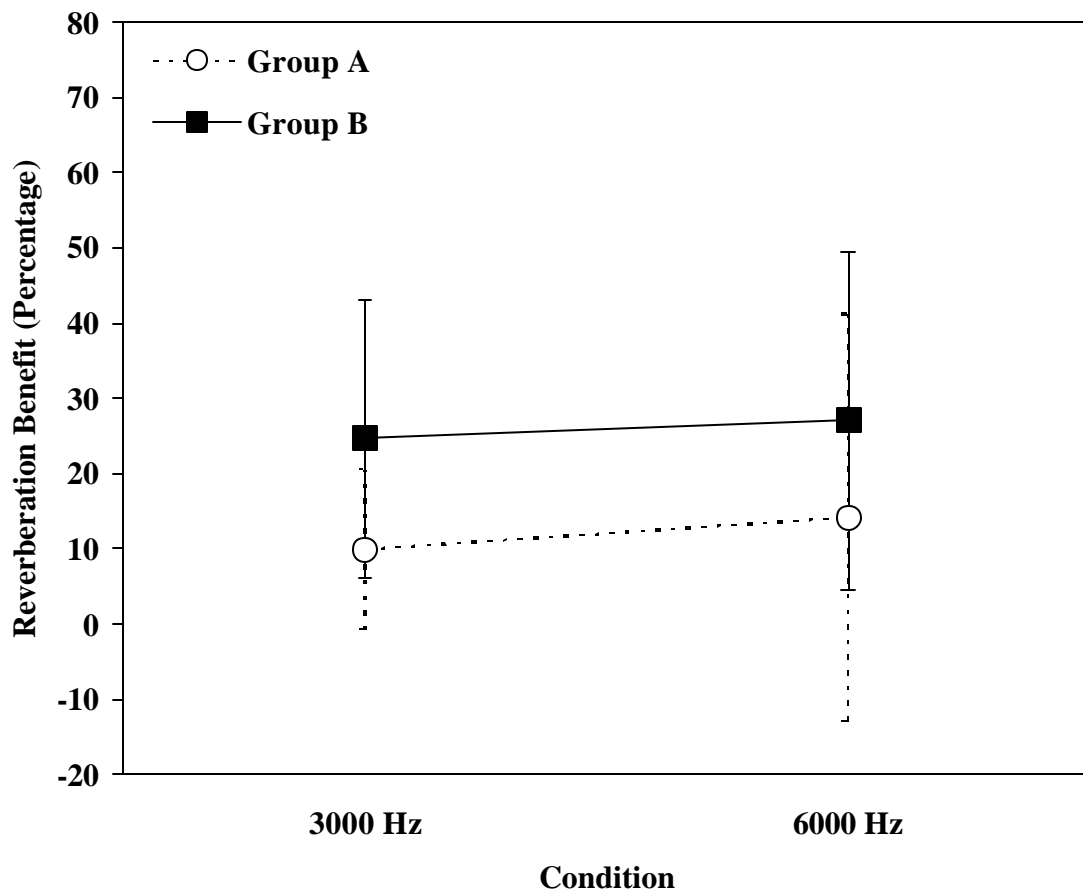


Figure 6: Reverberation benefit for each bandwidth

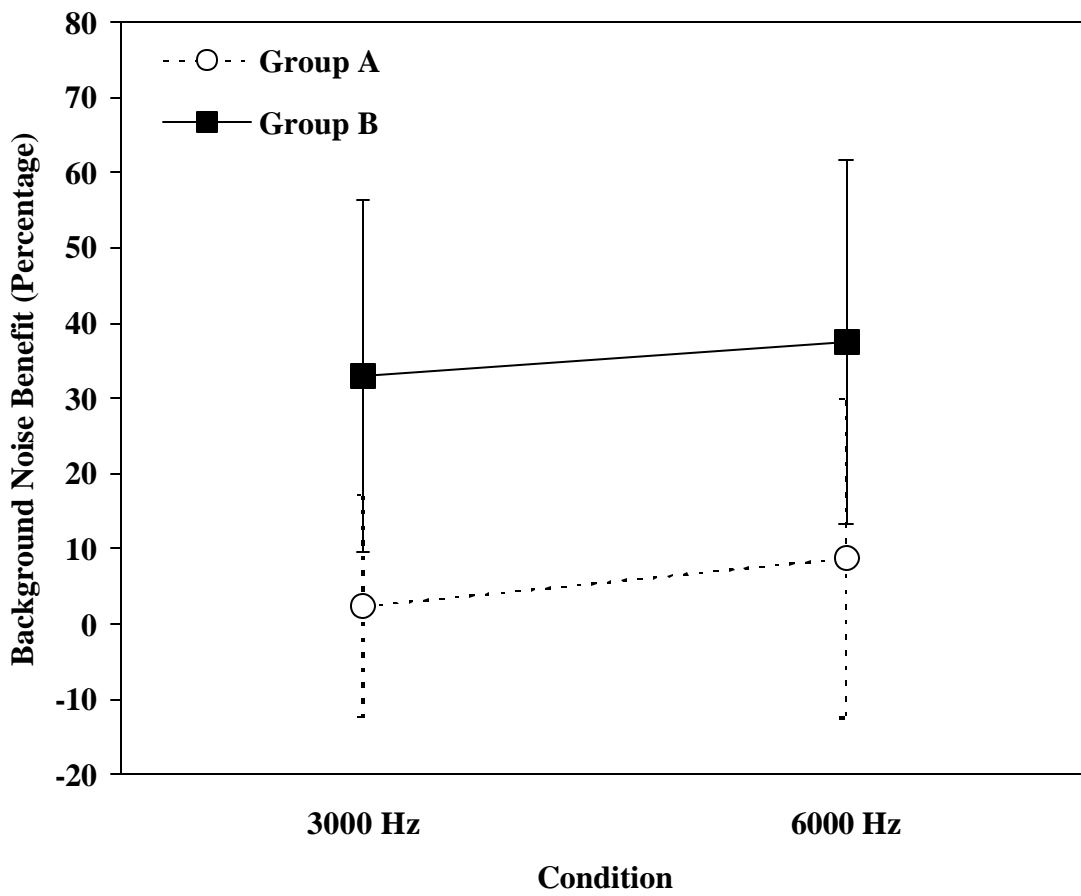


Figure 7: Background noise benefit for each bandwidth

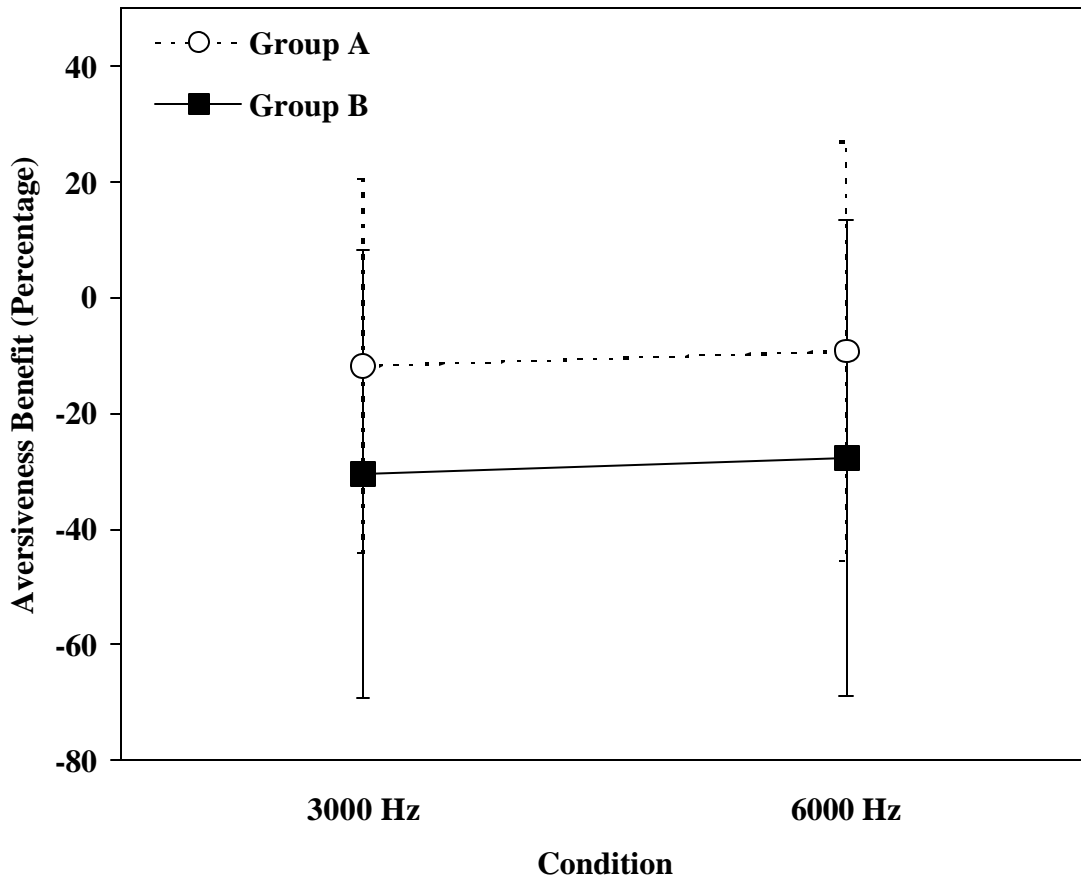


Figure 8: Aversiveness benefit for each bandwidth

dependent variable was RV benefit score. The within subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed no significant main effects for bandwidth [$F(1,15) = 0.442, p > 0.05$], for group [$F(1,15) = 2.502, p > 0.05$], or for the bandwidth by group interaction [$F(1,15) = 0.037, p > 0.05$]. These results indicated that each group reported similar benefit in reverberant environments for each bandwidth condition. These results further indicated that increasing the hearing instrument bandwidth did not significantly improve reported benefit in reverberant conditions for either group.

A two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group on subjective benefit in the background noise subscale (BN). The dependent variable was BN benefit score. The within subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two levels (A and B). The analysis revealed significant main effects for group [$F(1,15) = 11.423, p < 0.05$]. No significant main effects were evident for the bandwidth [$F(1,15) = 1.078, p > 0.05$] or for the bandwidth by group interaction [$F(1,15) = 0.033, p > 0.05$]. These results indicated that group B reported significantly more benefit in background noise than group A for each bandwidth condition. These results further indicated, however, that increasing the hearing instrument bandwidth did not significantly improve reported benefit in background noise for either group.

Lastly, a two-way analysis of variance was performed to determine the effects of hearing instrument bandwidth and group on subjective benefit in the aversiveness subscale (AV). The dependent variable was AV benefit score. The within-subject factor was hearing instrument bandwidth with two levels (3 kHz and 6 kHz). The between-subject factor was group with two

levels (A and B). The analysis revealed no significant main effects for bandwidth [$F(1,15) = 0.139, p > 0.05$], for group [$F(1,15) = 1.253, p > 0.05$], or for the bandwidth by group interaction [$F(1,15) = 0.000, p > 0.05$]. These results indicated that each group reported similar benefit in aversive environments for each bandwidth condition. These results further indicated that increasing the hearing instrument bandwidth did not significantly improve reported benefit in aversive conditions for either group.

Subjective performance was also evaluated at the completion of each subject's participation in the study via questionnaire. Analysis of the exit questionnaire indicated that 94% of the subjects reported receiving benefit from the hearing instruments. In addition, 65% of the subjects reported a preference for the 6 kHz condition, 23% of the subjects preferred the 3 kHz condition and 12% of the subjects had no preference. Subjects were also asked to evaluate their ability to hear speech in quiet and in noise during the project. In quiet, 76% of the subjects reported better performance during the 6 kHz condition while 12% reported better performance during the 3 kHz condition (12% were undecided). In noise, 54% of the subjects reported better performance during the 6 kHz condition while 24% reported better performance during the 3 kHz condition (24% were undecided). These results suggest that the 6 kHz condition was preferred by the majority of the subjects overall, in quiet and in noise.

CHAPTER VI

DISCUSSION

PROBE MICROPHONE MEASURES

Probe microphone measures were made to verify the response characteristics of each hearing instrument for each condition. The results of the probe microphone measures indicated that the mean output levels for each condition were significantly different. The measurements also revealed that group B's relative AI was significantly greater than group A's for each bandwidth. The measurements further indicated that the aided AI values were significantly greater for the 6 kHz condition than the 3 kHz condition for each group. Therefore, any potential objective and/or subjective performance differences may be attributed to the difference between the conditions.

EXPERIMENT I

The first purpose of the present study was to determine if amplifying beyond 3 kHz resulted in increased objective benefit in hearing impaired listeners. The results indicated that Group B received significantly more benefit in quiet than Group A for each bandwidth condition; however, increasing the bandwidth did not significantly improve benefit in quiet for either group. The results further indicated that Group B received significantly more benefit in noise than Group A for each bandwidth condition and that increasing the bandwidth significantly improved benefit in noise for each group.

Results of testing in quiet may be explained by the articulation index theory. AI theory predicts a speech intelligibility rating of excellent with 95 to 100% of the sentences understood for listeners with AI scores ranging from 0.4 to 1.0 (ANSI S3.5-1969). Therefore, hearing-impaired listeners are able to correctly identify speech information when as little as 40% of the

speech spectrum is audible. Stated differently, hearing-impaired listeners are able to “fill-in-the-blanks” of the speech spectrum in quiet to correctly identify the information due to the redundancy of the speech signal.

In the present study, the mean unaided AI score for Group A was 0.84 and the mean unaided AI score for Group B was 0.47. Given this, AI theory would predict that listeners in each group would correctly identify sentence information in quiet when unaided; therefore, amplification could only produce minimal improvements due to ceiling effects. Consequently, unaided testing in quiet resulted in a mean score of 98% correct for Group A and a mean score of 83% correct for Group B. Aided testing in quiet resulted in a mean score of 97% correct for Group A and 92% correct for Group B for each bandwidth condition. Therefore, it is reasonable to postulate that performance was not significantly improved in quiet with either bandwidth condition due to the fact excellent identification ability was evident in the unaided condition.

AI theory may also explain the results of testing in noise. The presence of background noise masks speech cues that are audible in the quiet condition thereby reducing the AI of the listener in noise. Given this, AI theory would predict that listeners in each group would encounter greater difficulty identifying sentence information in noise than in quiet when unaided. AI theory would also predict that listeners with greater degrees of hearing loss would be more significantly impacted by the introduction of noise because their residual AI values could be approaching the 0.4 AI criteria for excellent identification ability. Therefore, amplification may produce identification improvements in noise if the audibility of the speech spectrum is enhanced.

In the present study, testing in noise was conducted using the CST and the HINT. The CST was conducted using a +6 dB signal-to-noise ratio whereas the HINT was conducted using

an adaptive procedure to determine the 50% identification level. Unaided CST in noise testing resulted in a mean score of 90% correct for Group A and a mean score of 64% correct for Group B. In addition, unaided HINT testing resulted in a mean score of -0.6 dB for Group A and a mean score of 3.1 dB for Group B. These results suggested that the introduction of noise resulted in greater identification degradation for listeners in Group B than for listeners in Group A.

Aided CST in noise testing resulted in a mean score of 89% correct for Group A for each bandwidth condition; however, aided CST testing in noise for Group B resulted in mean scores of 74% and 80% correct for the 3 kHz and 6 kHz conditions respectively. Aided HINT testing for Group A resulted in a mean HINT score of 1.0 dB for the 3 kHz condition and a mean HINT score -0.4 dB for the 6 kHz condition. Conversely, aided HINT testing for Group B resulted in a mean HINT score of 2.2 dB for the 3 kHz condition and a mean HINT score of 0.5 for the 6 kHz condition. These results indicate that amplifying beyond 3 kHz resulted in significant improvement in noise for each group. Therefore, it is reasonable to postulate the significant improvement in noise may be attributed to the increased AI score that would result from expanding the bandwidth of the hearing instrument.

Although results of testing in noise indicated that amplifying beyond 3 kHz resulted in statistically significant improvement for each group, these results should be viewed with caution. Further examination of the data suggests objective benefit associated with expanding the bandwidth of the hearing instrument may be directly related to the degree of hearing loss of the user. For example, examination of the mean data for Group A indicated similar performance in noise on each test (CST and HINT) in the unaided, 3 kHz, and 6 kHz conditions. This, again, may be attributed to the fact listeners in Group A had less hearing loss than listeners in Group B.

As a result, noise levels utilized in the present study may not have been sufficient enough to significantly degrade identification ability in the unaided condition. Consequently, the amplification provided in each bandwidth condition provided comparable performance.

Conversely, noise levels utilized in the present study may have been sufficient enough to significantly degrade identification ability in the unaided condition for listeners in Group B. As a result, expanding the bandwidth of the hearing instrument resulted in improved performance in noise. In fact, examination of the mean data for Group B indicated that performance improved in each aided condition on each test (CST and HINT). Although the group by bandwidth interactions were not statistically significant for either test in noise, the interaction approached significance for the CST testing in noise ($p = 0.069$). In addition, interaction results for the HINT may have been skewed by the fact Group A's performance was poorer in the 3 kHz condition than in the unaided condition but was improved in the 6 kHz condition. This resulted in a decrease in performance relative to the unaided condition for the 3 kHz setting and an increase in performance relative to the unaided condition for the 6 kHz setting. Therefore, expanding the bandwidth resulted in a statistically significant improvement in performance in noise for Group A; however, performance was comparable to that of the unaided condition. Future research efforts should continue to investigate the effects of degree of hearing loss on benefit with high-frequency amplification.

The second purpose of this study was to evaluate whether the benefit of amplifying beyond 3 kHz was dependent on degree of loss. For this study the amount of benefit was similar for each bandwidth suggesting that the amount of benefit is not dependent on degree of loss. These results are in contrast to the findings that suggest benefit from amplifying higher frequencies diminishes once the hearing loss exceeds approximately 55 dBHL and is therefore

dependent on degree of loss (Byrne, D. 1986; Hogan, C.A. & Turner, C.W. 1998; Turner, C.W. & Cummings, K.J. 1998; Sullivan et al. 1992). Schwartz et al. (1979), as well as Sullivan et al. (1992), found that benefit of amplification for higher frequencies were not dependent on degree of loss. However, the additional amplification was reported to be detrimental to sound quality.

One possible explanation for the differences in findings is that previous studies were performed under ideal conditions in laboratory settings that simulated hearing instruments. This study actually utilized custom hearing instruments and accounted for acclimatization to the hearing instruments and the time it takes for the brain to adjust to new signals.

EXPERIMENT II

The third purpose of this study was to determine whether amplifying beyond 3 kHz resulted in increased subjective benefit in hearing impaired listeners. Stated differently, if the objective measures resulted in increased benefit by adding the extra bandwidth, would the subjective data reflect the improvement? The APHAB results revealed that group B received more benefit than group A for ease of communication and background noise but not for reverberation or aversiveness. The results further indicated that increasing the bandwidth did not significantly improve benefit for either group. In other words, amplifying beyond 3 kHz did not increase subjective benefit according to the APHAB. However, the APHAB alone may not be sensitive enough to increases in bandwidth.

The exit questionnaire was geared more specifically to the issues. 65% of the subjects overall reported a preference for the 6 kHz condition vs. 23% for the 3 kHz condition. One of the fitting difficulties of CIC instruments, especially when accompanied by greater hearing loss, is dealing with feedback. To combat this issue, the feature feedback cancellation was turned on for 8 out of 17 subjects with 7 of the 8 subjects being in group B. This feature enables the hearing

instrument to locate the frequency region where the feedback occurs and send in the opposite phase signal to cancel out the feedback while preserving the gain. All subjects who preferred the 3 kHz condition were part of group B and had the feedback cancellation feature turned on. One possible explanation as to why they preferred the 3 kHz condition may be that feedback was more of an issue for them than the other subjects. This may have been the case for subject 5 who preferred the 3 kHz condition overall but reported doing better in quiet and noise with condition 6 kHz. Subject 5 also reported that 6 kHz condition produced a better sound quality.

In quiet, 76% of the subjects reported better performance during the 6 kHz condition vs. 12% during the 3 kHz condition. Again, the subjects who performed better in the 3 kHz condition were all in group B, had feedback cancellation turned on, and also overall had a preference for the 3 kHz condition. One possible explanation may be that the feedback only affected their performance during the 6 kHz condition enabling them to perform better during the 3 kHz condition when feedback wasn't an issue. This may have been the case for Subject 9 who liked the 3 kHz condition better overall but stated in the miscellaneous comments section that he would have like the 6 kHz condition better if he didn't have to deal with feedback.

In noise, 54% of the subjects reported better performance during the 6 kHz condition vs. 24% during the 3 kHz condition. Again, the subjects who performed better in the 3 kHz condition were all in group B with the exception of one. All group B subjects had feedback cancellation turned on and overall had a preference for the 3 kHz condition. The one group A subject did not have feedback cancellation turned on and was our least hearing impaired subject. However, the subject's place of employment may explain the preference for the 3 kHz condition. This subject works in a restaurant setting where the hearing instrument may have amplified too much of the extraneous noise present causing a decline in performance. This subject's rating of

noisy situations may have not been representative of different environments filled with noise rather geared specifically toward a restaurant environment. Overall, results from the exit questionnaire suggest that the 6 kHz condition was preferred by the majority of the subjects overall, both in quiet and in noise.

CONCLUSION

In summary, this study's findings suggest that amplifying beyond 3 kHz may result in increased objective benefit in hearing-impaired listeners in noise but not quiet and also that the objective benefit obtained may be dependent on degree of loss. This may also suggest that patients who have hearing impairment similar to group A's may not benefit from conventional hearing instruments that only amplify out to 3 kHz. Subjective benefit did not improve by adding the extra bandwidth according to the APHAB but did show improvement according to the exit questionnaire. This may suggest that the APHAB is not a sensitive enough test to reflect benefit between different hearing instrument settings.

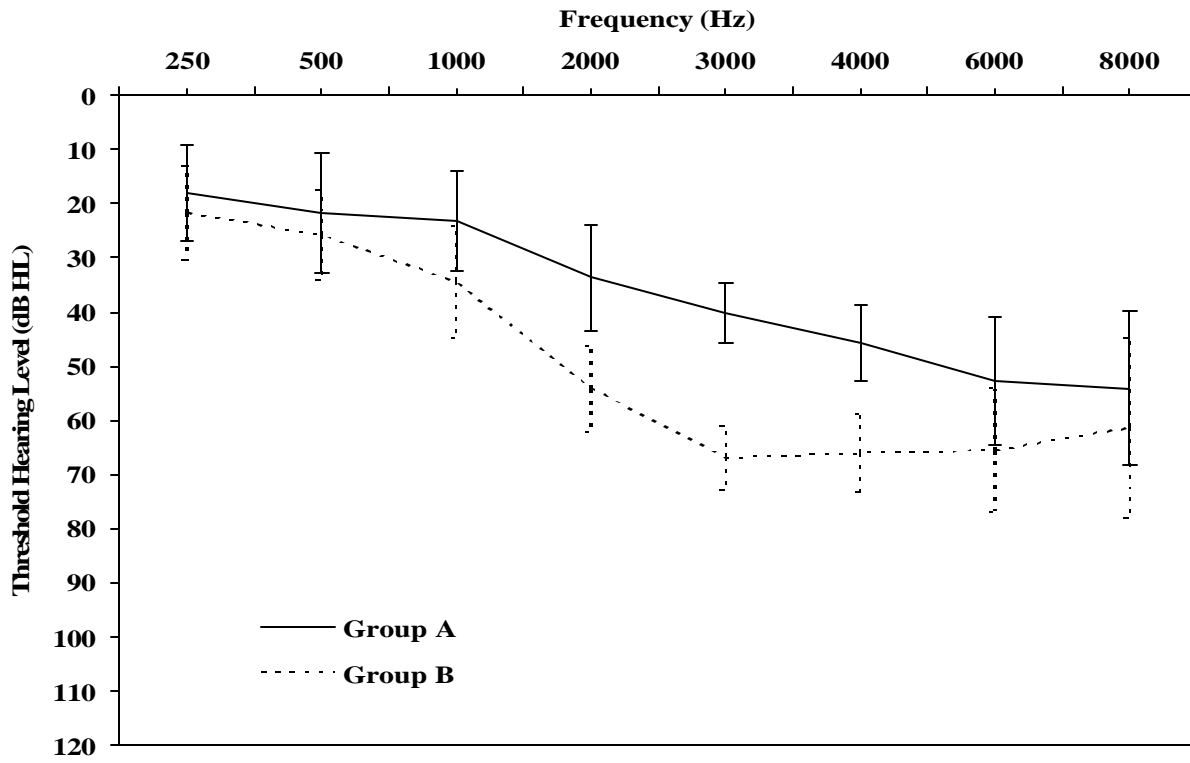
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APPENDIX A:
AVERAGE THRESHOLDS



APPENDIX B:
EXIT QUESTIONNAIRE

Subject _____

1. Do you feel you benefit from the hearing aids?
Yes No

2. Which condition (1st 6 weeks or 2nd 6 weeks) did you like better?
1st 2nd ND

3. Which condition allowed you to hear speech better in quiet situations?
1st 2nd ND

4. Which condition allowed you to hear speech better in noisy situations?
1st 2nd ND

5. Which condition produced a better sound quality?
1st 2nd ND

6. Did you experience any unpleasant sounds throughout the course of the 12 weeks?
Yes No

7. If yes, which condition were the sounds the most unpleasant?
1st 2nd ND

8. If you had to pay for the hearing aids, what amount would you be willing to pay for both instruments?
3000 4000 5000 6000 Other _____

9. Do you feel that the benefit you received from the hearing aids are worth the cost? (6000) Yes No

10. On average how long did you wear the hearing aids per day?
<4 4-6 hrs 6-8 hrs >8 hrs Other _____

Miscellaneous Comments:

VITA

Erica Lynn Fleck is a native of Illinois, born in Rushville on October 3, 1979. She received a Bachelor of Arts in communication sciences and disorders from Augustana College in Rock Island, Illinois, in May 2001. She began her clinical fellowship year in audiology while finishing her Master of Arts program at Louisiana State University. Ms. Fleck is currently employed at Acadian Hearing and Balance Center in Lafayette and plans to obtain her doctorate in the field of audiology upon completion of her clinical fellowship year.