ABSTRACT

Comparing Effects of Frequency Maps on Sentence Perception Between Simulated Bimodal and Electric Acoustic Stimulation Hearing

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Speech understanding with a cochlear implant (CI) and hearing aid (HA) on either the opposite ear (i.e., bimodal) or the same ear (i.e., EAS) produces a considerable synergistic effect. While many bimodal and EAS users experience significant benefit, others gain little or no benefit or experience interference. One potential contributor to this variability is that the effect of different degrees of residual hearing thresholds in HA ears on the maps has not been seriously considered. Another challenging aspect of previous bimodal and EAS studies is the difficulty of precisely interpreting the results due to different testing, audiologic components, demographic variables, bandwidths, filtering cutoff frequencies, and slopes for either HA or CI ear. Each of these factors precludes controlled comparisons in real bimodal and EAS patients. Existing bimodal and electric acoustic stimulation (EAS) studies suggest highly mixed results regarding frequency fitting maps. This study evaluated various frequency maps on the benefit of bimodal and EAS hearing in sentence perception using acoustic simulation. Results indicated that the optimal map was similar across bimodal and EAS hearing configurations but was influenced by the upper-frequency bounds of residual hearing in the acoustic ear. Results also showed that bimodal and EAS benefit in sentence perception is also similar regardless of signal-to-noise ratio (SNR). In this study, using simulations of bimodal and EAS hearing with normal hearing (NH) listeners, we determined the optimal frequency maps, based on sentence perception scores by adjusting acoustic and electric boundary frequencies.

APPROVED BY DIRECTOR OF HONORS THESIS:

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COMPARING EFFECTS OF FREQUENCY MAPS ON SENTENCE PERCEPTION BETWEEN SIMULATED BIMODAL AND ELECTRIC ACOUSTIC STIMULATION HEARING

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CHAPTER ONE

Introduction

One of the most significant problems in cochlear implant (CI) research is maximizing the spectral and temporal representation of speech for CI patients. One way to accomplish this task is to deliver important speech acoustics to CI patients who retain some residual acoustic hearing in either the implanted ear or in the non-implanted ear. Both bimodal, a condition in which one ear is implanted with a CI and the contralateral ear is fitted with a hearing aid (HA) and EAS, when one ear is fitted for a device that delivers both acoustic amplification and electric stimulation to the same ear, is known to provide a considerable synergistic benefit in speech perception. This gain is defined as a performance difference in speech perception with bimodal hearing and with a better ear alone. This synergistic benefit in speech perception can be accomplished by providing amplification in the low-frequencies and electric stimulation in the mid-to-high frequencies (Ching, van Wanrooy, & Dillon, 2007; Dorman, Gifford, Spahr, & McKarns, 2008; Gifford et al., 2017; Irving et al., 2014; Kong & Carlyon, 2007). The idea behind bimodal hearing is that the loss of sensory cells can be compensated for utilizing electric stimulation in the mid-to high-frequency range in combination with acoustic stimulation of the remaining low-frequency areas of the cochlear receptors. The bimodal hearing option is even more attractive considering the transmission loss of low-frequency information in CIs due to a limited insertion depth of electrode array in the cochlea. However, it should be noted that even though the majority of bimodal users received a significant benefit in speech perception, a portion of the subjects received little to no benefit (Gstoettner et al., 2006; James et al., 2006; Kiefer et al., 2005; Kong & Braida, 2011). A primary reason for this variability is the use of less optimized clinical frequency maps for their CIs and HAs.

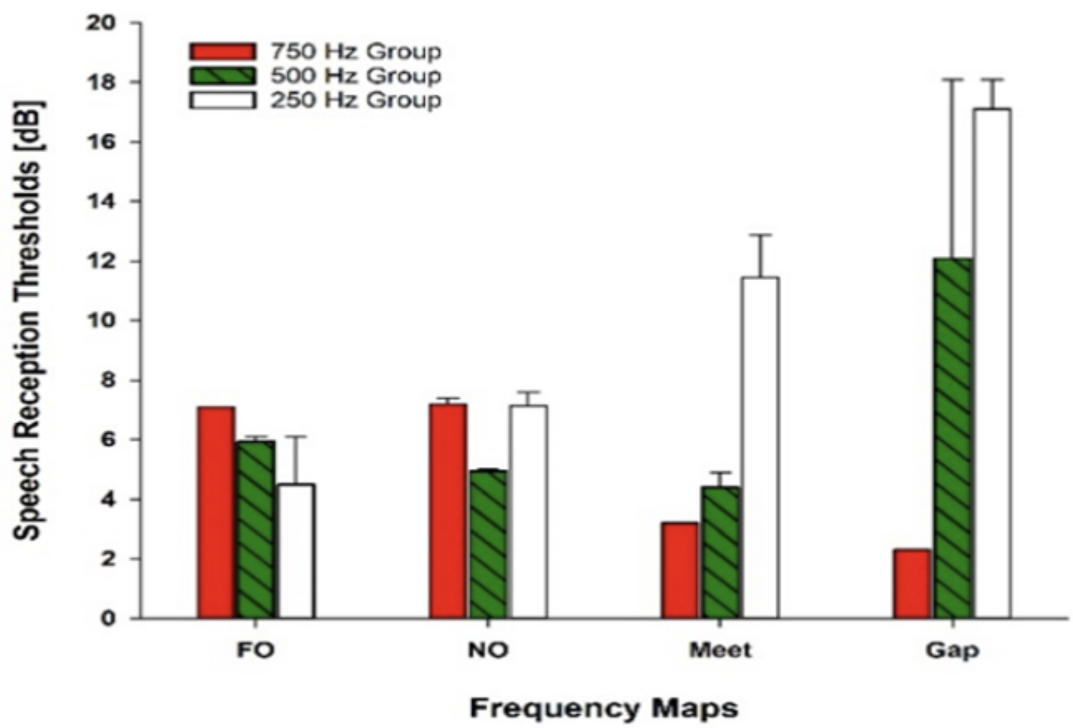

Figure 1: SRT results for sentences with four different maps in three NH subjects. Lower SRT Scores indicate better speech perception.

In the last 10 years, bimodal and EAS research has shown a highly mixed picture of clinical maps. Current commercially available CI programming interfaces default to a “Narrow Overlap (NO)” map, where the lower frequency edge of electrical stimulation slightly overlaps on the frequency that unaided hearing thresholds reach, either ⩾ 65dB HL (Helbig et al., 2011; Nopp & Polak, 2010) or ⩾ 80dB (Fraysse et al., 2006; Gantz et al., 2009; James et al., 2006; Simpson, McDermott, Dowell, Sucher, & Briggs, 2009). However, many published works have reported that Meet maps (i.e., the highest frequency stimulated acoustically meets the lowest frequency stimulated electrically) provided consistent, superior performance over the other types of maps (Fraysse et al., 2006; Gantz et al., 2009; James et al., 2006; Karsten et al., 2013; Simpson et al., 2009). Numerous studies reported the Gap map (i.e., frequency gap between an HA ear and a CI ear) provided greater benefit in speech perception and was also subjectively preferred by the majority of the listeners (Dorman & Gifford, 2010; Roland, Gantz, Waltzman, & Parkinson, 2016; Woodson, Reiss, Turner, Gfeller, & Gantz, 2010). Recently, Gifford and colleagues claimed that Full Overlap (FO) mapping (i.e., frequency overlap between a HA ear and a CI ear) provides optimal performance (Gifford et al., 2017). One potential factor for a mixed picture of frequency maps is that the effect of different degrees of residual hearing thresholds in HA ears on the maps has not been seriously considered. Differentiating the effect of residual hearing thresholds on the frequency map in combined electric and acoustic hearing is important clinically because the degree of residual hearing in the HA ear affects functional hearing significantly, making their aural rehabilitation treatment goals highly individualized (Dorman & Gifford, 2017; Dubno, Dirks, & Langhofer, 1982; Reiss, Eggleston, Walker, & Oh, 2016; Zhang, Heinz, Bruce, & Carney, 2001). Another challenging aspect of these previous studies is the difficulty in precisely interpreting the results due to different testing conditions, audiologic components other than hearing thresholds, and different demographic variables. Such controlled comparisons cannot easily be made in real bimodal and EAS patients.

To explicitly control audiometric and demographic differences within and between subjects, we collected pilot data using acoustic simulation of bimodal hearing with three normal hearing (NH) listeners. The listeners were tested with the Institute of Electrical and Electronics Engineers (IEEE) sentence perception using four different frequency maps: FO, NO, Meet, and Gap. The results show that the frequency map highly depends on the unaided hearing threshold at frequencies ⩽ 750 Hz (Figure 1). We simulated the acoustic ear with three common configurations of residual hearing thresholds (hearing loss ⩽ 250, 500, or 750 Hz) found in bimodal patients. The four maps were created by manipulating the lower edge of frequency used for the CI ear simulation. Results showed that listeners with acoustic residual hearing at frequencies ⩽ 250 Hz with severe to profound hearing loss at higher frequencies reached their best performance with the FO map. The Meet map provided the best outcomes for listeners with acoustic residual hearing of ⩽ 500 Hz and profound hearing loss in high frequencies. The Gap map provided the best outcomes for listeners with acoustic residual hearing at frequencies ⩽ 750 Hz. In this project, using acoustic simulation of bimodal hearing, we generated additional data that will serve as an efficient clinical guideline for optimization of frequency maps for bimodal patients on an individual basis.

The objective of this project was to determine how bimodal and EAS frequency maps are dependent upon the degree of residual hearing thresholds in the HA ear. This will allow us to identify the optimal frequency map for each bimodal and EAS listening circumstance to enhance the benefit of device use. This will help develop psychoacoustic frequency mapping tools so that HAs, CIs, and EAS devices can be better mapped to achieve greater bimodal benefit in speech perception. The results from this project are expected to improve both quality of life for bimodal users and satisfaction for hearing device users. The results will also facilitate the creation of a more efficient audiologic rehabilitation framework for current and future electric and acoustic hearing device users. Our central hypothesis was that the optimal frequency map depends on the degree of residual hearing loss at the frequency below 750 Hz in the HA ear. To achieve our objective, we tested three specific hypotheses. Hypothesis 1: FO map will be optimal for individuals with residual hearing loss up to 250 Hz in the HA ear. Hypothesis 2: Meet map will be optimal for individuals with residual hearing up to 500 Hz in the HA ear. Hypothesis 3: Gap map will be optimal for individuals with residual hearing up to 750 Hz or higher in the HA ear.

CHAPTER TWO

Methods

Participants and Power Analysis

Twelve adult NH subjects participated in this bimodal acoustic simulation study. They were tested with each of the four frequency maps (FO, NO, Meet, and Gap). In our previous study with a sample size of 10 adult NH listeners (Yoon et al., 2019), there was a significant main effect of the simulated residual hearing threshold with a statistical power of 80%. Using this information, a minimum of 10 participants ould provide a power of 80% in detecting a difference of 0.45 between the null hypothesis correlation of 0.2 and the alternative hypothesis correlation of 0.68 at a significance level of 0.05 in a two-tailed hypothesis test. Anticipating a typical attrition rate of 20%, we recruited 15 adult NH listeners. This power analysis is not sex-specific. All subjects were native speakers of American English and were required to have hearing thresholds better than 20 dB HL (hearing level) at audiometric frequencies from 0.25 to 8 kHz. We used a pure-tone test to verify eligibility based on thresholds. All subjects provided informed consent and all procedures were approved by the Baylor University Insti-tutional Review Board.

Stimuli

72 lists of IEEE sentences produced by a female talker were used (Rothauser EH, 1969). Each list has ten sentences. This quantity allows us to avoid redundancy of the same sentence list per subject because there were a total of 60 conditions (4 maps x 3 listening modes × 5 SNRs; see details in Procedure below).

Acoustic Simulation for Creating Different Bimodal Frequency Maps

For the acoustic simulation, we created the three most common residual hearing thresholds found in bimodal and EAS patients (i.e., 250, 500, and 750 Hz) using band-pass filtering (Dorman et al., 2008; James et al., 2006; Yoon, Li, & Fu, 2012). Each IEEE sentence was filtered with a fixed lower cutoff frequency of 50 Hz and each of the upper cutoff frequencies of 250, 500, and 750 Hz (20th order Butterworth filters; 240 dB/octave). The lower edge of the acoustic residual hearing (i.e., 50 Hz) is known as the lowest frequency region to carry some speech cues (Liberman, 1954). For the electric simulation, we used an 8-channel noise vocoder with a fixed output frequency range of 1000-7938 Hz (see Figure 2 below). The lower edge frequency (i.e., 1000 Hz) corresponds to a cochlear location of a 21 mm insertion of a CI electrode array according to Greenwood function (Greenwood, 1990), which is also the average insertion depth of CI electrode array for CI patients (Gifford et al., 2017; Karsten et al., 2013). The upper edge frequency of 7938 Hz is similar to the highest input frequency commonly used in commercial CI speech processors. An eight-channel simulation was selected to match the typical number of activated channels in current commercial CI speech processors. Noise vocoder was selected instead of using sine vocoder to include the effect of channel interaction, one of the technical limitations in the current CI speech processors, for the CI simulation. The temporal envelope from each IEEE sentence was extracted from each of the output channels by half-wave rectification and low-pass filtering (4^{th} order Butterworth filter with 160 Hz envelope cutoff). The temporal envelope from each band was used to modulate corresponding noise bands. The modulated noise bands were summed and their output was adjusted to have the same long-term root-mean-square energy as the input speech signal.

Different frequency maps were created by adjusting the lower edge of electric frequency input to the simulated CI ear, relative to the upper edge of acoustic residual hearing. Figure 2 illustrates the frequency setups used to create four different frequency maps. For the Full Overlap (FO) map, a fixed input frequency range (188-7983 Hz) to the simulated CI ear was used for all three acoustic residual hearing ranges. This frequency range includes the maximum frequency ranges that current major CI speech processors can present. As a result, frequency overlap between the HA ear and the CI ear is 62 Hz, 312 Hz, and 562 Hz for the acoustic residual hearing at 250, 500, and 750 Hz, respectively. The Narrow Overlap (NO) map was created by adjusting the lower electric frequency to begin at 10% below the upper edge of acoustic residual hearing, which is a current default setting that commercially available CI programming interfaces adapt (Fraysse et al., 2006; Gantz et al., 2009; Helbig et al., 2011; James et al., 2006; Nopp & Polak, 2010; Simpson et al., 2009). Thus, with the NO map, the frequency overlap between the HA ear and the CI ear is 25, 50, 75 Hz for the acoustic residual hearing at 250, 500, and 750 Hz, respectively. For the Meet map, the lower electric frequency was mapped to begin at the upper edge of acoustic residual hearing. For the Gap map, the lower electric frequency was chosen to begin at 50% above the upper edge of acoustic residual hearing. As a result, the frequency gap between the HA ear and the CI ear is 125, 250, and 375 Hz for the acoustic residual hearing at 250, 500, and 750 Hz, respectively.

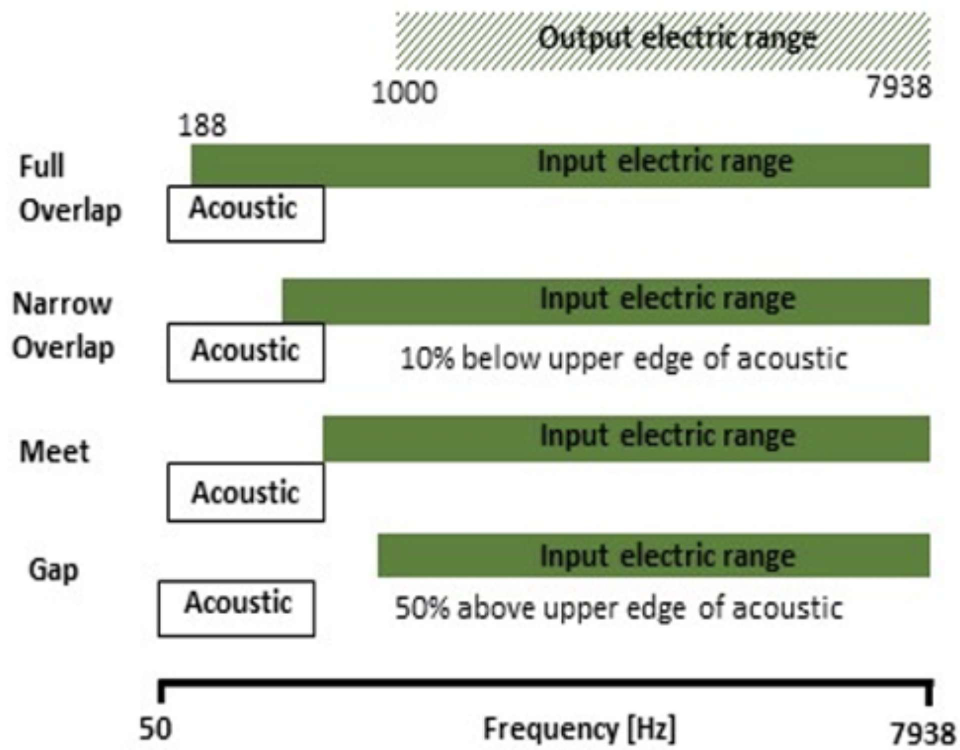

Figure 2: Diagram of the four experimental conditions. Full Overlap uses a fixed frequency range, 188-7938 Hz; Narrow Overlap (current clinical map), lower electric frequency begins at 10% below upper edge of acoustic; Meet, lower electric frequency begins at the upper edge of acoustic; Gap, lower electric frequency begins at 50% above upper edge of acoustic.

Procedures

IEEE Sentence recognition was measured with simulated acoustic alone, simulated electric alone, both in quiet and in steady-state noise (1000-Hz low-pass cutoff frequency, –12 dB/oct) at +10, 0, -10, and -20 dB signal-to-noise ratio (SNR). Bilateral and unilateral presentations of IEEE sentences were controlled by MATLAB (The MathWorks, 2017). The SNR was calculated in terms of the long-term root-mean-square of the speech signal and noise. Speech and noise were mixed at the target SNR. The selection of the SNRs is based on our preliminary studies in NH listeners, showing that ceiling and floor effects were minimized (Yoon et al., 2019). The combined speech and noise signal was delivered via an audiometer (GSI Audiostar Pro) to headphones (Sennheiser HD 600).

Subjects were seated in a single-walled sound-treated booth (Industrial Acoustics Company) directly facing the microphone (0° azimuth) one meter away. The output level of the audiometer was set at either 60 dB or 65 dB sound pressure level for each listening condition according to the Cox Loudness Rating scale (Cox, 2005) in response to 10 sentences from IEEE list one in quiet. Before formal testing, 20-minute familiarization was given for each frequency map using IEEE lists 2-6. The first six lists were excluded from formal testing. During testing, a sentence list was selected (without replacement), and a sentence was randomly selected from within the list (without replacement) and presented to the subject who then would repeat the sentence as accurately as possible. A trained experimenter scored responses by clicking the words correctly repeated using a computer mouse. No trial-by-trial feedback was provided during testing. Data were compared with the sentence perception scores with each of the new maps and was compared with the score with the clinical map (i.e., NO). The complete test protocol was randomized and counterbalanced across subjects and should take approximately three hours.

Identification of Bimodal Benefit and Better-Ear Alone

Our previous study shows that simulated CI-alone performance is significantly better than simulated HA-alone performance over SNRs (Yoon et al., 2019), therefore sentence recognition scores were averaged over SNRs. Better-ear alone was determined by comparing the average scores over SNRs between CI alone and HA alone. Then, bimodal benefit was calculated using the ratiometric equation, “(” to include absolute performance differences in the better ear-alone across subjects.

CHAPTER THREE

Results and Analysis

Expected Outcomes

In our pilot data (Figure 1), we predicted that the optimal map would be consistent with a specific subject group. Based on this trend, we expected to find that most participants would fall into one of these maps. We also expected that some may deviate from this pattern.

Results

Effects of Frequency Maps and Residual Hearing in Bimodal Conditions

One of the important clinical questions in the bimodal research is which frequency map is optimal for bimodal users who have different configurations of residual hearing (i.e., A250, A500, and A750 Hz) in their hearing aid ear. We analyzed bimodal data to answer to this question using two-way repeated measure analysis of variance (ANOVA) with two repeated independent factors residual hearing and frequency map at each SNR. Figure 3 shows the mean percent correct scores in sentence perception under bimodal hearing at each SNR.

For -6 dB SNR (top left panel), the analyses showed the residual hearing significantly impacted sentence perception, $F(2,66)=14.10$, $p < 0.001$, meaning that mean percent scores significantly improved with better residual hearing. The analyses also showed that the frequency map significantly influenced sentence perception, $F(3,66)=5.04$, $p = 0.006$. Pairwise multiple comparison with Bonferroni correction for the frequency map factor showed that only two pairs were significant within the A250 Hz condition, as indicated by asterisks ($p < 0.05$). That is, FO map provided a significantly higher sentence perception, compared to Meet and Gap maps for bimodal users who have useful residual hearing at frequency less than 250 Hz. For bimodal users with residual hearing up to 500 Hz and 750 Hz, sentence perception scores are not significantly different across the four frequency maps. The analyses indicated that there is no significant interaction between the residual hearing and the frequency map, $F(6,66)=1.90$, $p = 0.09$. For 0 dB SNR, there were significant effects of both residual hearing, $F(2,66)=12.97$, $p < 0.001$, and frequency map, $F(3,66)=6.68$, $p = 0.001$, on mean percent scores. Interactions between the two factors were also significant, $F(6,66)=3.98$, $p = 0.002$. For +6 dB SNR, there were significant effects of both residual hearing, $F(2,66)=16.15$, $p < 0.001$, and frequency map, $F(3,66)=6.86$, $p = 0.001$, on mean percent scores. Interactions between the two factors were also significant, $F(6,66)=4.39$, $p < 0.001$. For 0 dB SNR and + 6 dB

SNR, pairwise multiple comparison with Bonferroni correction showed that any map could be recommended for A250 Hz because perception scores were not significantly influenced by the different maps. For A500 Hz, either NO, Meet, or Gap map may be recommended, while for A750 Hz, either NO or Meet may be recommended. In the quiet condition, there were significant effects of both residual hearing, $F(2,66)=46.69$, $p < 0.001$, and frequency map, $F(3,66)=5.28$, $p = 0.001$, on mean percent scores. Interactions between the two factors were also significant, $F(6,66)=7.66$, $p < 0.001$. Pairwise multiple comparisons showed that any map could be recommended for A750 Hz because perception scores were not significantly influenced by the different maps. For A250 Hz, Meet map be recommended, while for A500 Hz, Gap map be recommended.

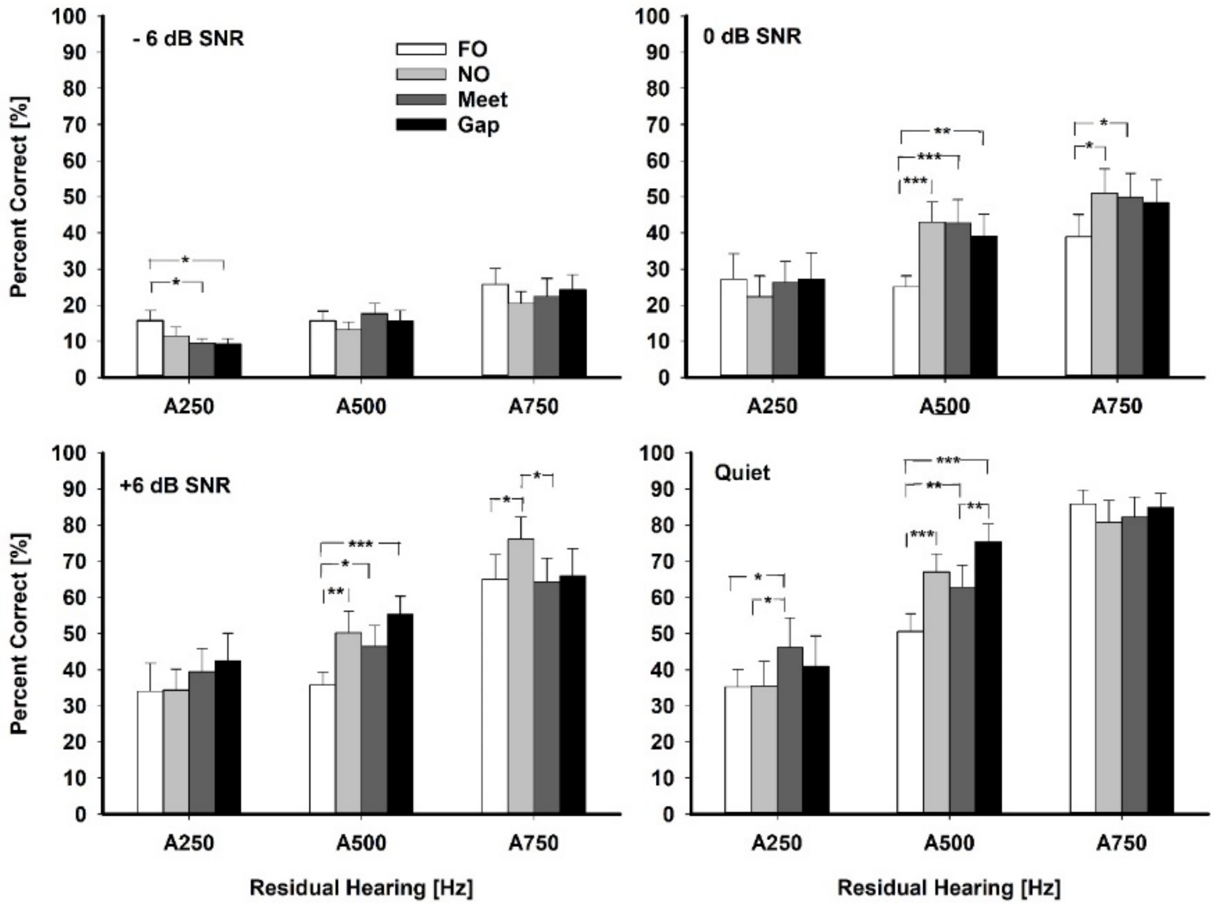

Figure 3: Mean sentence percent correct for bimodal listening at each SNR for as a function of residual hearing (250, 500, and 750 Hz) and frequency map (FO, NO, Meet, and Gap). *** indicates $p < 0.001$. ** indicates $p < 0.01$ and * indicates $p < 0.05$.

Effects of Frequency Maps and Residual Hearing in EAS Conditions

In this section, we tried to answer to the question: which frequency map is the optimal for EAS users with different configurations of residual hearing (i.e., A250, A500, and A750 Hz). A two-way repeated measure ANOVA with two repeated independent factors (residual hearing and frequency map) was performed as each SNR. Figure 5 shows the mean percent correct in sentence perception under EAS hearing at each SNR.

For -6 dB SNR (top left panel), the analyses showed the residual hearing significantly impacted sentence perception, $F(2,66)=6.63$, $p=0.005$, meaning that mean percent scores significantly improved with better residual hearing. The analyses also showed that the frequency map significantly influenced sentence perception, $F(3,66)=3.68$, $p = 0.04$. Pairwise multiple comparison with Bonferroni correction for the frequency map factor showed that any map can be recommended for A250. However, NO for A500 and Gap for A750 may be recommended because percent scores were the highest with these maps, as indicated by asterisk. The analyses indicated that there is significant interaction between the residual hearing and the frequency map, $F(6,66)=3.58$, $p = 0.004$. For 0 dB SNR, there were significant effects of both residual hearing, $F(2,66)=18.76$, $p < 0.001$, and frequency map, $F(3,66)=4.36$, $p = 0.011$, on mean percent scores. Interactions between the two factors were also significant, $F(6,66)=3.39$, $p = 0.006$. Pairwise multiple comparisons showed that any map could be recommended for A250 Hz because perception scores were not significantly influenced by the different maps. For A500 Hz, NO map may be recommended, while for A750 Hz, Gap map may be recommended. For +6 dB SNR, there were significant effects of both residual hearing, $F(2,66)=44.23$, $p < 0.001$, and frequency map, $F(3,66)=24.17$, $p < 0.001$, on mean percent scores. Interactions between the two factors were also significant, $F(6,66)=7.59$, $p < 0.001$. In the quiet condition, there were significant effects of both residual hearing, $F(2,66)=47.65$, $p < 0.001$, and frequency map, Map: $F(3,66)=8.29$, $p < 0.001$, on mean percent scores. However, interaction between the two factors was not significant, $F(6,66)=0.91$, $p=0.48$. For both +6 dB SNR and quiet conditions, pairwise multiple comparisons showed that any map could be recommended for A750 Hz because perception scores were not significantly influenced by the different maps. For both A250 and A750 Hz, Gap map may be recommended.

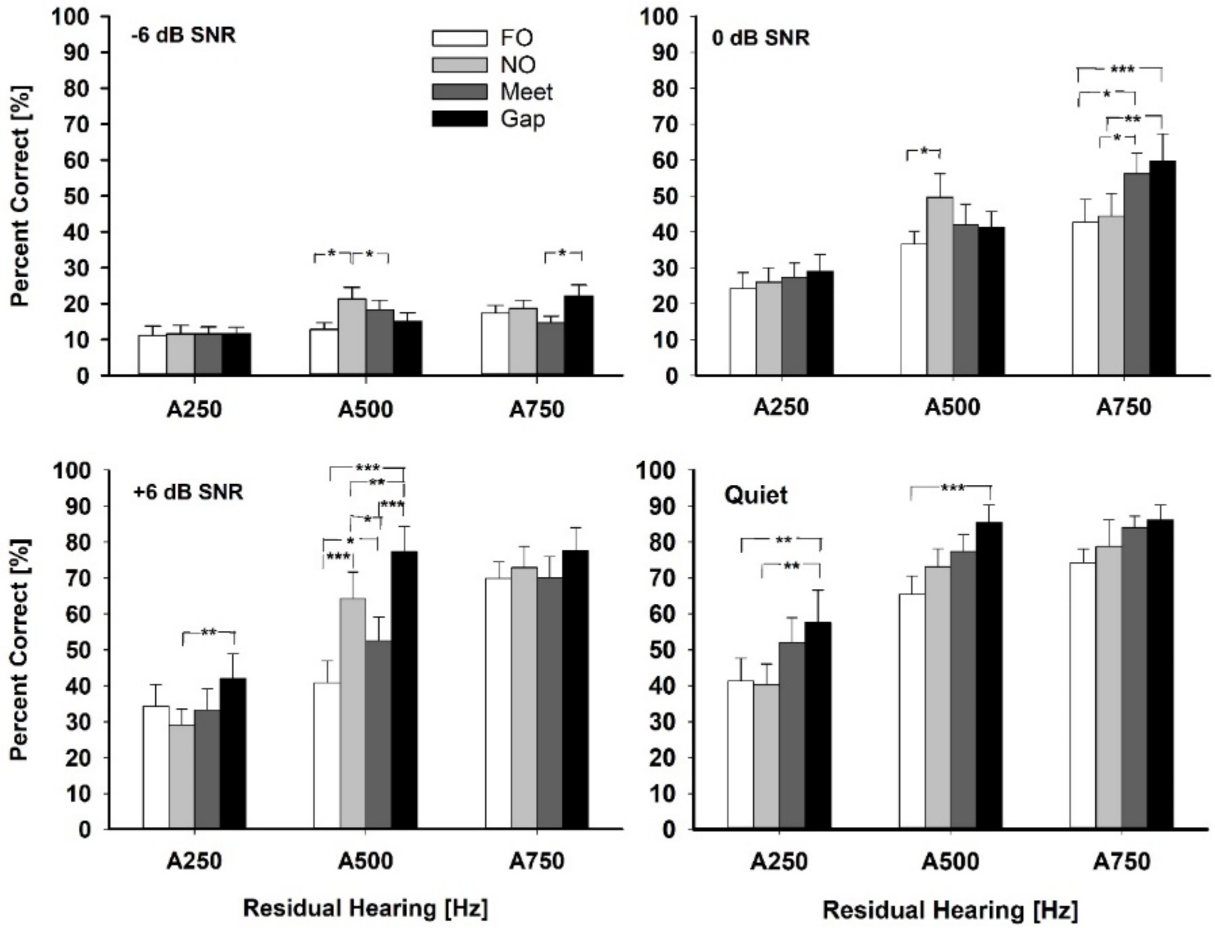

Figure 4: Mean sentence percent correct for EAS listening at each SNR for as a function of residual hearing (250, 500, and 750 Hz) and frequency map (FO, NO, Meet, and Gap). *** indicates p < 0.001. ** indicates p < 0.01 and * indicates p < 0.05.

Comparing Optimal Bimodal and EAS Maps

Our second clinical questions for the study were (1) Is the optimal map same or different for bimodal and EAS hearing technologies (2) If different, which map may be recommended in terms of their configurations of residual hearing? To answer these questions, we analyzed the same data presented in Figures 3 and 4, but as a function of the frequency map and of hearing technology (i.e., bimodal vs EAS). A two-way ANOVA with two independent factors (frequency map and hearing technology) was performed at each SNR. To answer the questions, our pairwise multiple comparison analyses were focused on comparing percent scores between the two hearing technologies with each map. The results were presented in Figures 5-7 below for A250 Hz, A500 Hz, and A750 Hz, respectively.

Figure 5 shows percent scores as a function of the frequency maps and hearing technology for A250 Hz case. The statistical analyses showed that there were no significant effects of both frequency map and hearing technology on sentence perception regardless of SNR. There were marginal differences in percent scores between the two hearing technologies across the frequency map at each SNR, but these differences were not statistically significant. It means that any map could be recommended to either bimodal or EAS users who have useful residual hearing up to 250 Hz. Here are formal statistical analyses. Effects of both frequency map, $F(3,88)=0.85$, $p = 0.47$, and, hearing technology, $F(1,88)=0.10$, $p=0.95$, on mean percent scores were not significant at − 6dB SNR. Interaction between the two factors was also not significant, $F(3,88)=1.12$, $p = 0.34$. For the SNR = 0 dB, effects of both frequency map, $F(3,88)=0.19$, $p = 0.90$, and, hearing technology, $F(1,88)=0.05$, $p=0.81$, were not significant. Interaction was also not significant, $F(3,88)=0.13$, $p = 0.95$. For the SNR = +6 dB, effects of both frequency map, $F(3,88)=0.99$, $p = 0.40$, and, hearing technology, $F(1,88)=0.42$, $p=0.52$, were not significant. Interaction was not significant as well, $F(3,88)=0.13$, $p = 0.94$. In quiet condition, effects of both frequency map, $F(3,88)=1.59$, $p = 0.20$, and, hearing technology, $F(1,88)=2.70$, $p=0.11$ were not significant. Interaction was not significant as well, $F(3,88)=0.31$, $p = 0.82$.

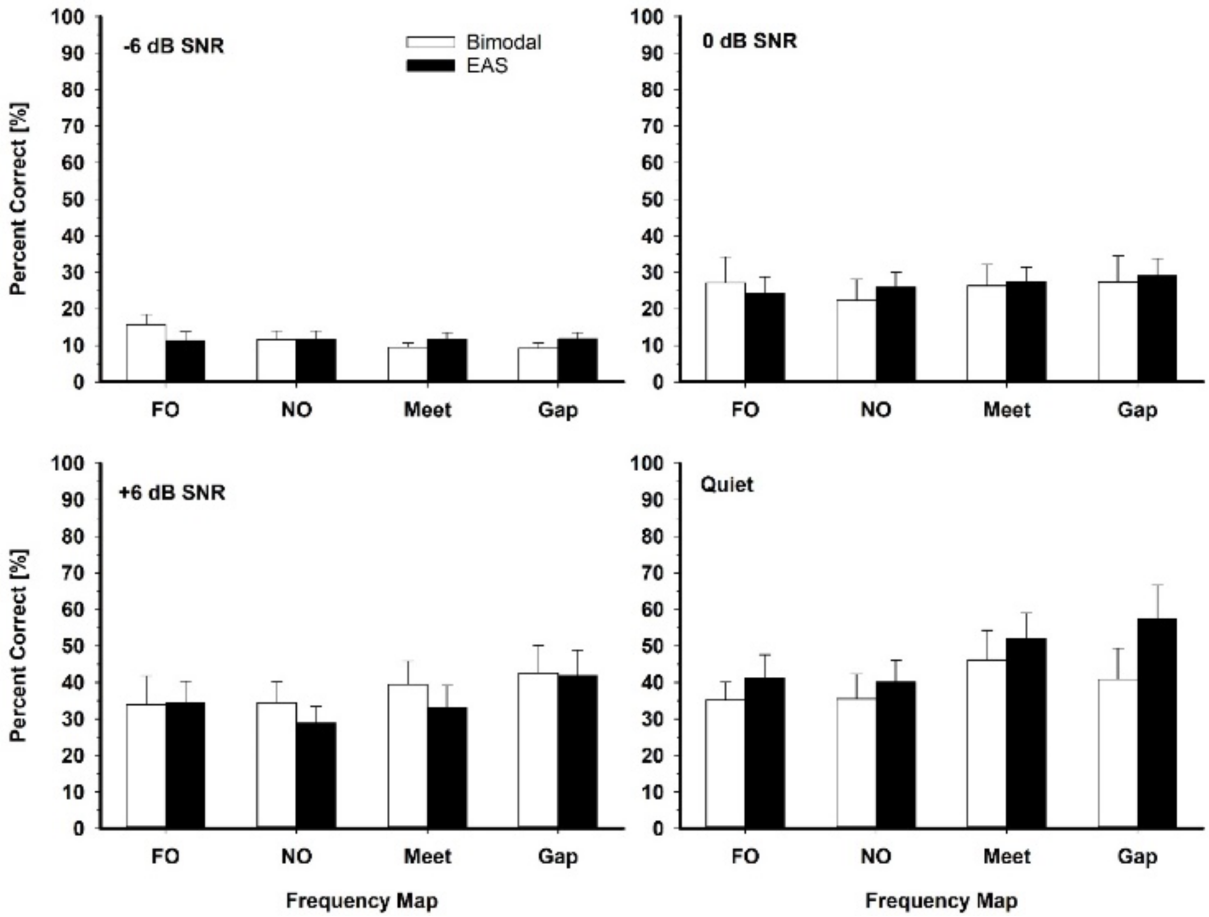

Figure 5: Comparisons in percent correct for sentence perception between bimodal and EAS listening for A250 Hz condition as a function of frequency map at each SNR.

Figure 6 shows percent scores for A500 Hz in terms of the frequency maps and hearing technology. There was a trend that EAS hearing provided higher sentence perception over the four maps at each SNRs. The statistical analyses showed no significant effects of both frequency map and hearing technology on sentence perception at -6 dB and 0 dB SNRs but significant effects at two higher SNRs.

Effects of both frequency map, $F(3,88)=0.87$, $p = 0.46$, and hearing technology, $F(1,88)=0.52$, $p =0.47$, on mean percent scores were not significant at – 6dB SNR. Interaction between the two factors was also not significant, $F(3,88)=1.52$, $p = 0.21$. For 0 dB SNR, effects of both frequency map, $F(3,88)=3.00$, $p = 0.05$, and, hearing technology, $F(1,88)=1.72$, $p =0.19$, were not significant. Interaction was also not significant, $F(3,88)=0.50$, $p = 0.68$. For +6 dB SNR and quiet condition, significant main effects of both factors were observed. For the SNR = +6 dB, effects of both frequency map, $F(3,88)=7.70$, $p < 0.001$, and, hearing technology, $F(1,88)=7.52$, $p =0.007$, were significant. However, interaction was not significant, $F(3,88)=0.85$, $p = 0.47$. Pairwise multiple comparisons showed that significant differences between two hearing technologies occurred for only Gap map, as indicated by asterisks. In quiet condition, effects of both frequency map, $F(3,88)=6.45$, $p <0.001$, and hearing technology $F(1,88)=9.82$, $p =0.002$ were significant. However, interaction was not significant, $F(3,88)=0.33$, $p = 0.80$. Pairwise multiple comparisons showed that significant differences between two hearing technologies occurred for FO and Gap maps, as indicated by asterisks. These results suggest that different maps could provide higher sentence perception in relatively quiet environment between bimodal and EAS users even though they have useful residual hearing up to 500 Hz.

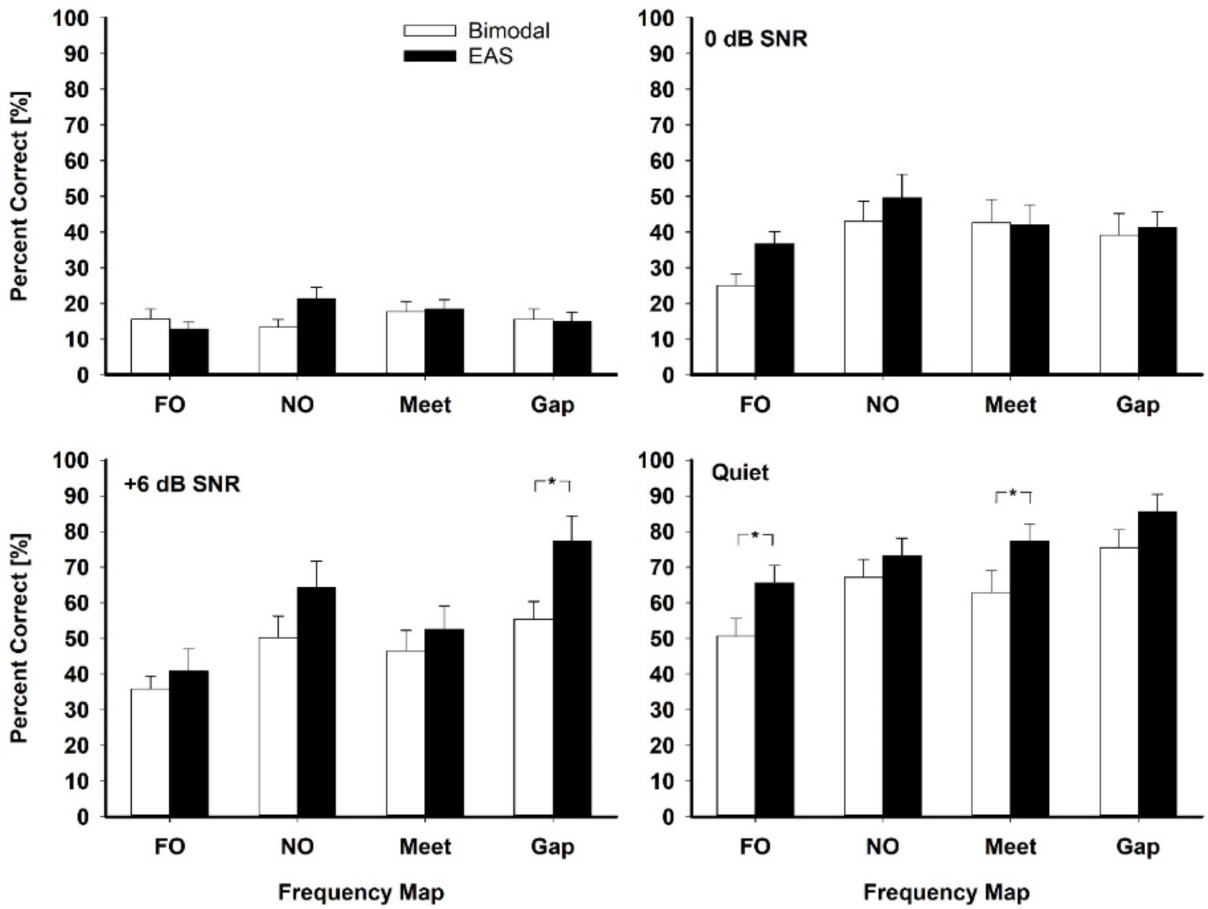

Figure 6: Comparisons in percent correct for sentence perception between bimodal and EAS listening for A500 Hz condition as a function of frequency map at each SNR. * indicates $p < 0.05$.

Figure 7 shows percent scores for A750 Hz case. The statistical analyses showed no significant effects of both frequency map and hearing technology on sentence perception regardless of SNR. There were marginal differences in percent scores between the two hearing technologies across the frequency map at each SNR, but these differences were not statistically significant. This result means that any map could be recommended to either bimodal or EAS users who have useful residual hearing up to 750 Hz. Here are formal statistical analyses. Effects of both frequency map, $F(3,88)=0.72$, $p = 0.54$, and, hearing technology, $F(1,88)=4.14$, $p = 0.05$, on mean percent scores were not significant at – 6dB SNR. Interaction between the two factors was also not significant, $F(3,88)=0.51$, $p = 0.68$. For 0 dB SNR, effects of both frequency map, $F(3,88)=1.76$, $p = 0.16$, and, hearing technology, $F(1,88)=0.66$, $p = 0.42$, were not significant. Interaction was also not significant, $F(3,88)=0.68$, $p = 0.57$. For +6 dB SNR, effects of both frequency map, $F(3,88)=0.63$, $p = 0.60$, and, hearing technology, $F(1,88)=1.11$, $p = 0.30$, were not significant. Interaction was not significant as well, $F(3,88)=0.48$, $p = 0.70$. In quiet condition, effects of both frequency map, $F(3,88)=0.65$, $p = 0.59$, and, hearing technology, $F(1,88)=0.60$, $p = 0.44$ were not significant. Interaction was not significant as well, $F(3,88)=0.81$, $p = 0.49$.

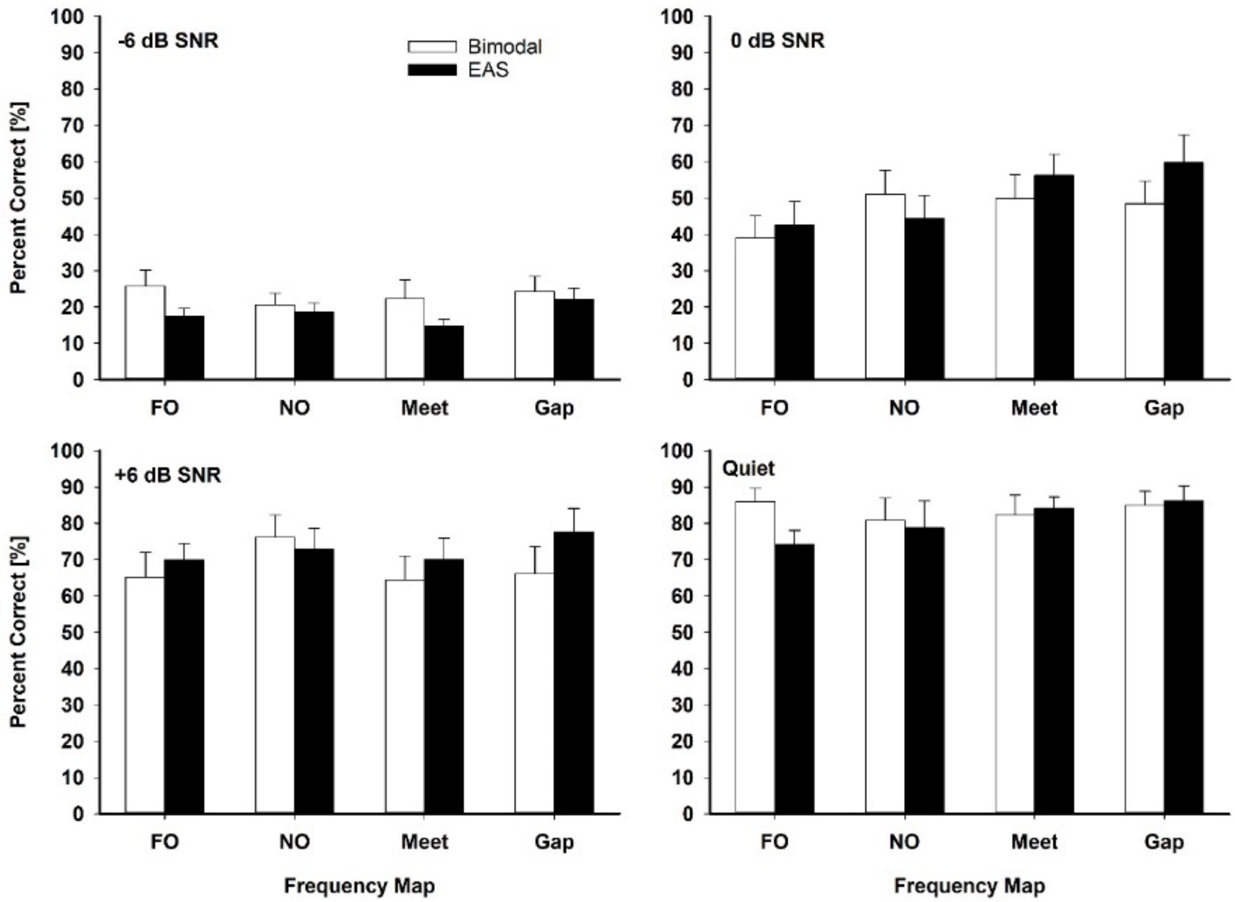

Figure 7: Comparisons in percent correct for sentence perception between bimodal and EAS listening for A750 Hz condition as a function of frequency map at each SNR.

Effects of Frequency Maps on Binaural Benefit

Our last clinical questions for the current study were (1) does binaural benefit in sentence perception depend on different frequency maps and (2) which hearing technology provides higher binaural benefit. Here, binaural benefit could be bimodal or EAS benefit depending on hearing technology. Binaural benefit is defined as percent score difference between bimodal or EAS hearing and better ear alone. Depending on subjects, the better ear alone could be HA ear alone or CI ear alone. Two-way ANOVA with two independent factors (frequency map and hearing technology) was performed at each SNR. To answer the questions, our pairwise multiple comparison analyses were focused on comparing binaural benefit between the two hearing technologies. The results were presented in Figures 8-10 below for A250 Hz, A500 Hz, and A750 Hz, respectively.

Figure 8 shows percent scores for A250 Hz case. The statistical analyses showed no significant effects of hearing technology on sentence perception regardless of SNR. There were marginal differences in binaural benefit between the two hearing technologies across the frequency map at each SNR, but these differences were not statistically significant. This result means that any map could provide similar binaural benefit for either bimodal or EAS users have useful residual hearing up to 250 Hz, regardless of the levels of background noise. Effects of both frequency map, $F(3,88)=1.19$, $p = 0.32$, and, hearing technology, $F(1,88)=0.04$, $p =0.84$ were not significant at – 6dB SNR. Interaction between the two factors was also not significant, $F(3,88)=0.84$, $p = 0.47$. For 0 dB SNR, effects of both frequency map, $F(3,88)=0.60$, $p = 0.62$, and, hearing technology, $F(1,88)=0.06$, $p =0.81$, were not significant. Interaction was also not significant, $F(3,88)=0.14$, $p = 0.94$. For +6 dB SNR, effects of both frequency map,

$F(3,88)=0.11$, $p = 0.95$, and, hearing technology, $F(1,88)=0.41$, $p =0.52$, were not significant. Interaction was not significant as well, $F(3,88)=0.13$, $p = 0.94$. In quiet condition, effects of both frequency map, $F(3,88)=0.65$, $p = 0.59$, and, hearing technology, $F(1,88)=2.65$, $p =0.11$were not significant. Interaction was not significant as well, $F(3,88)=0.31$, $p = 0.82$.

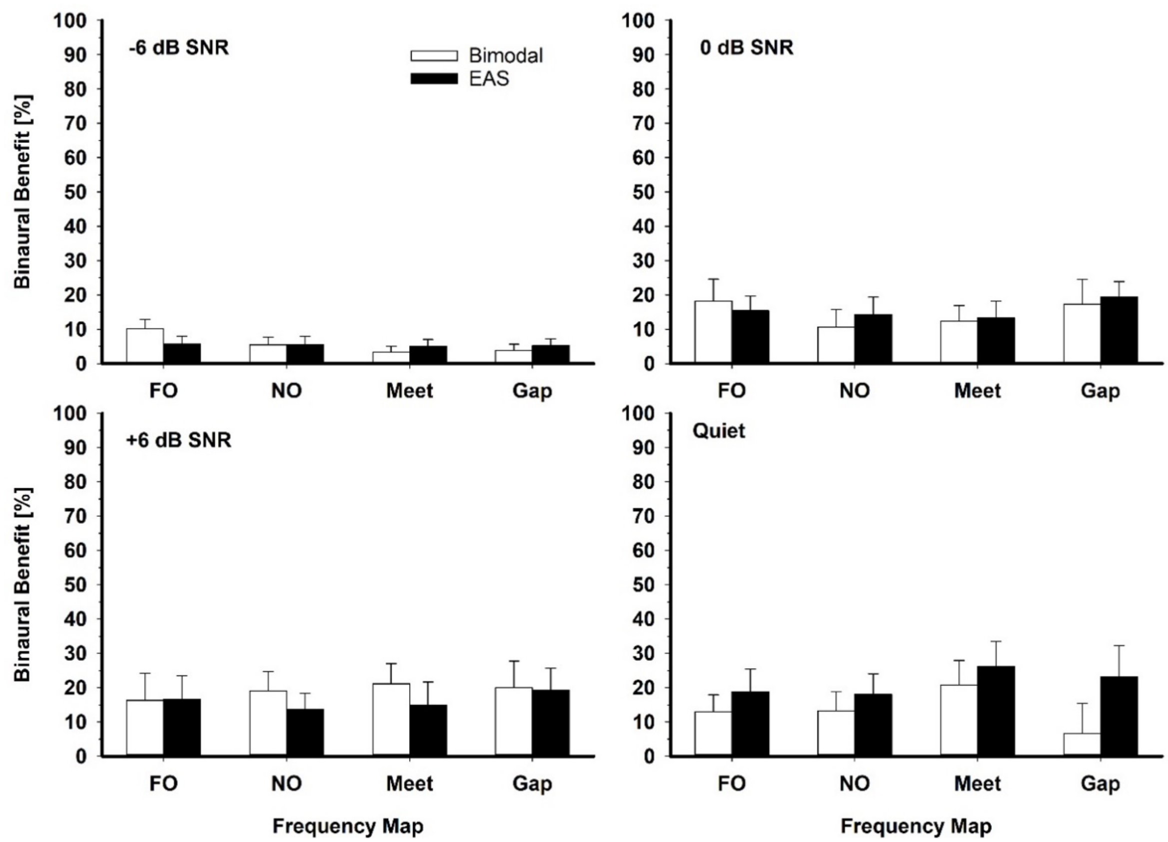

Figure 8: Comparisons in binaural benefit for sentence perception between bimodal and EAS listening for A250 Hz condition as a function of frequency map at each SNR.

Figure 9 shows percent scores for A500 Hz case. Marginal differences in binaural benefit were observed between the two hearing technologies across the frequency map at each SNR. Overall trend is that EAS benefit is relatively greater than bimodal benefit. The statistical analyses showed no significant effects of hearing technology on sentence perception at -6 dB SNR, 0 dB SNR, and in quiet conditions but significant effects at +6 dB SNR. For the SNR = +6 dB, effects of both frequency map, $F(3,88)=4.81$, $p = 0.004$, and, hearing technology, $F(1,88)=5.14$, $p = 0.03$, were significant. Pairwise multiple comparisons showed a significant difference between bimodal and EAS hearing within Gap map, as indicated by an asterisk. Interaction was not significant as well, $F(3,88)=1.26$, $p = 0.29$. Both frequency map, $F(3,88)=2.27$, $p = 0.08$, and hearing technology, $F(1,88)=0.52$, $p = 0.11$, did not affect mean percent scores significantly at – 6dB SNR. Interaction between the two factors was also not significant, $F(3,88)=2.42$, $p = 0.07$. For 0 dB SNR, frequency map, $F(3,88)=3.85$, $p = 0.05$, and hearing technology, $F(1,88)=0.52$, $p = 0.47$, did not affect mean percent scores significantly. Interaction was also not significant, $F(3,88)=1.22$, $p = 0.31$. In quiet condition, effects of both frequency map, $F(3,88)=0.42$, $p = 0.74$, and hearing technology, $F(1,88)=3.44$, $p = 0.07$ were not significant. Interaction was not significant as well, $F(3,88)=0.24$, $p = 0.87$. Figure 9 indicates that any map could provide similar binaural benefit for either bimodal or EAS users have useful residual hearing up to 500 Hz, regardless of the levels of background noise except for +6 dB SNR for Gap map.

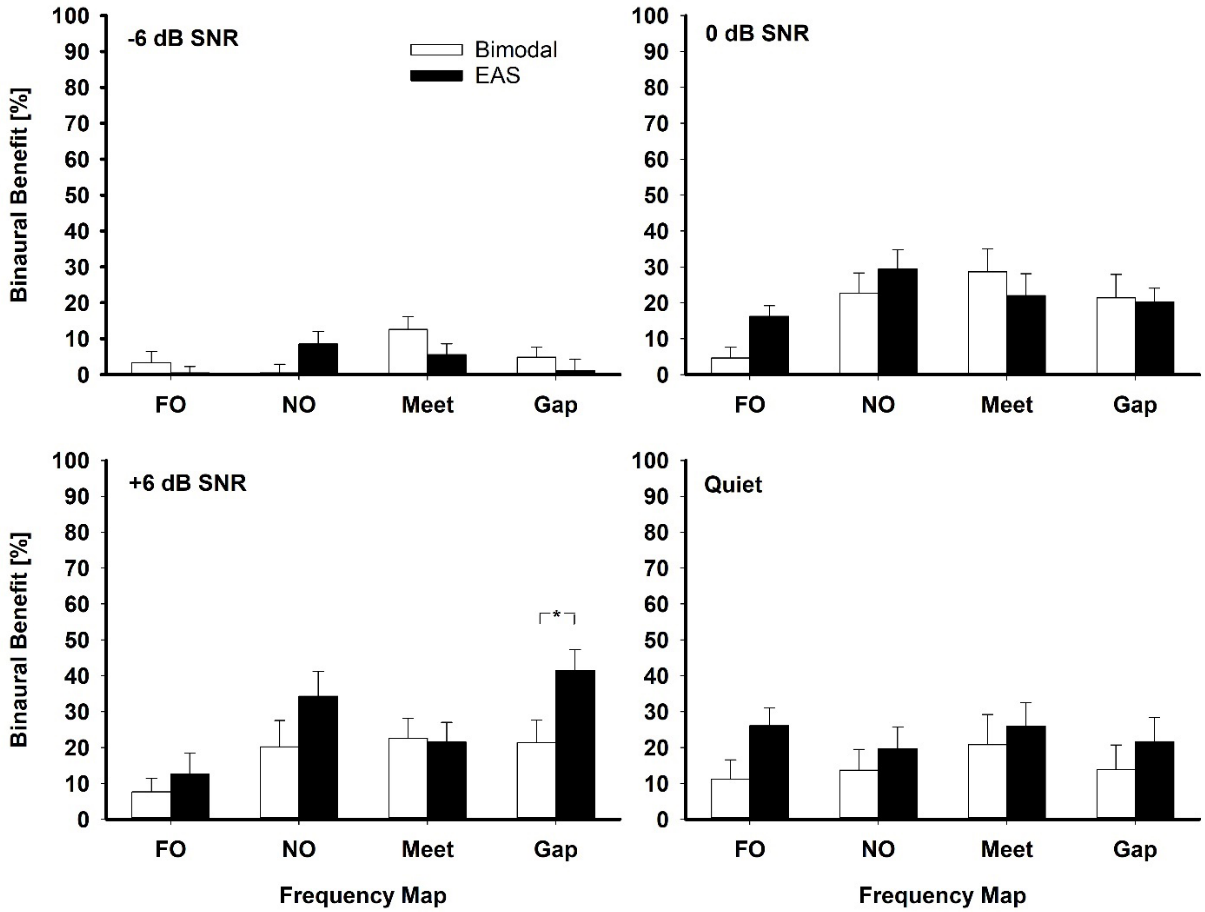

Figure 9: Comparisons in binaural benefit for sentence perception between bimodal and EAS listening for A500 Hz condition as a function of frequency map at each SNR. * indicates $p < 0.05$.

Figure 10 shows percent scores for A750 Hz case. Differences in binaural benefit were observed between the two hearing technologies across the frequency map at each SNR. Overall trend is that bimodal benefit is relatively greater than EAS benefit. The statistical analyses showed no significant effects of hearing technology on sentence perception at 0 dB SNR, +6 dB, SNR and in quiet conditions but significant effects at -6 dB SNR. Effects of both frequency map, $F(3,88)=0.55$, $p = 0.65$, and, hearing technology, $F(1,88)=8.10$, $p=0.006$, on mean percent scores were not significant at – 6dB SNR. Interactions between the two factors were also not significant, $F(3,88)=0.82$, $p = 0.48$. For the SNR = 0 dB, effects of both frequency map, $F(3,88)=4.34$, $p = 0.007$, and, hearing technology, $F(1,88)=0.17$, $p=0.68$, were not significant. Interaction was also not significant, $F(3,88)=0.58$, $p = 0.63$. For the SNR = +6 dB, effects of both frequency map, $F(3,88)=2.97$, $p = 0.04$, and, hearing technology, $F(1,88)=0.55$, $p=0.46$, were significant. Pairwise multiple comparisons showed a significant difference between bimodal and EAS hearing within Gap map, as indicated by an asterisk. Interaction was not significant as well, $F(3,88)=0.41$, $p = 0.75$. In quiet condition, effects of both frequency map, $F(3,88)=1.27$, $p = 0.29$, and hearing technology, $F(1,88)=3.14$, $p=0.08$, were not significant. Interaction was not significant as well, $F(3,88)=0.58$, $p = 0.63$. Figure 10 indicates that any map could provide similar binaural benefit for either bimodal or EAS users have useful residual hearing up to 750 Hz, regardless of the levels of background noise except for -6 dB SNR for Meet map.

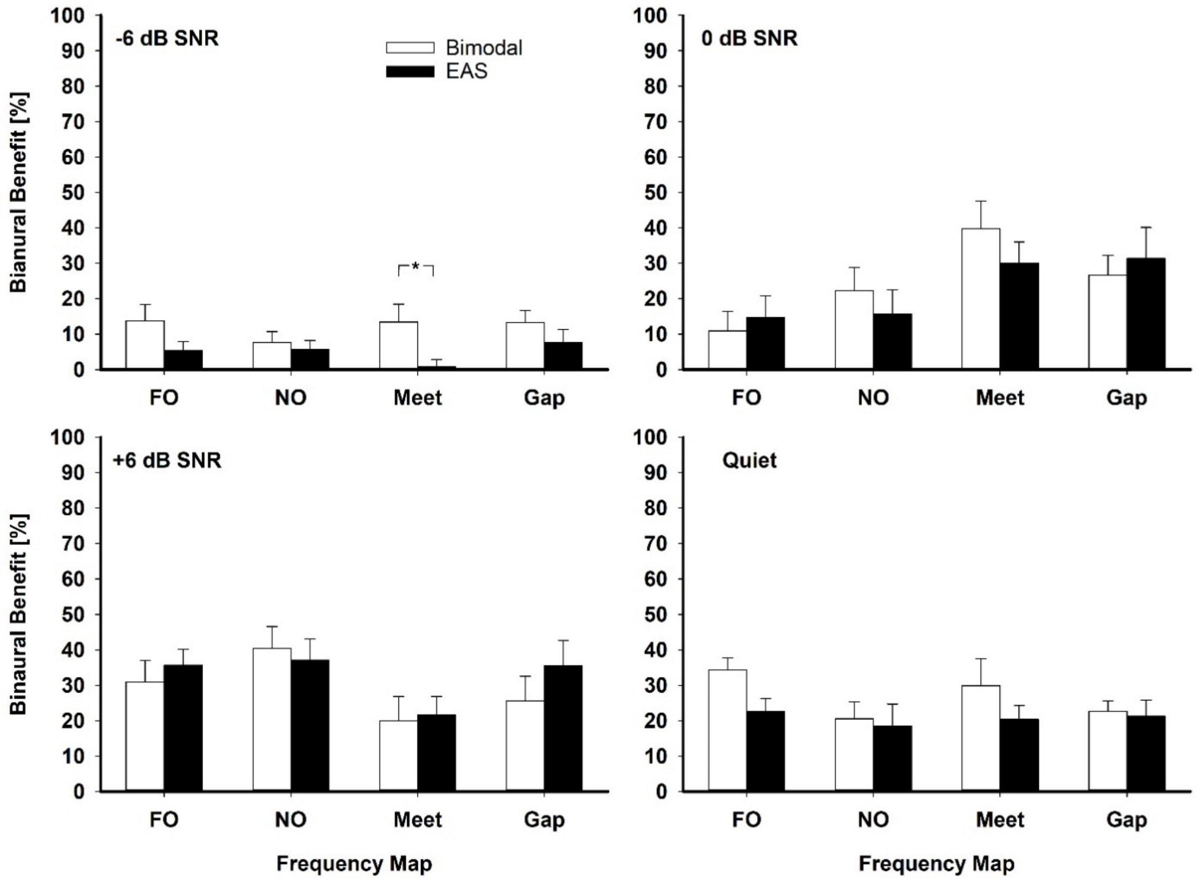

Figure 10: Comparisons in binaural benefit for sentence perception between bimodal and EAS listening for A750 Hz condition as a function of frequency map at each SNR. * indicates $p < 0.05$.

Statistical Analysis

To quantify the main effect of the independent variables (i.e., different maps, acoustic residual hearing thresholds, and SNR), a three-way repeated-measures analysis of variance with a significance of $p \leqslant .05$ was performed. As discussed in the Subject section, data were disaggregated according to sex and age and a correlation analysis was performed, but specific hypothesis testing about sex and age differences was not performed.

CHAPTER FOUR

Conclusions and Discussion

Conclusions

This study examined the effects of frequency maps on sentence perception in simulated bimodal and EAS listening conditions to determine the most effective map for three common residual hearing thresholds (A250 Hz, A500 Hz, A750 Hz) at four different signal-to-noise ratios (-6 dB, 0 dB, Quiet, 6 dB). Binaural benefit was compared between the two technologies at each threshold and signal-to-noise ratio. Sentence perception was measured using IEEE sentences controlled by MATLAB (MathWorks, 2017) and was scored based on the percentage of words repeated correctly following presentation. We independently analyzed the effects of these variables using a two-way repeated measure analysis of variance (ANOVA) with two independent factors (frequency map and hearing technology) at each SNR. Results indicate that the degree of residual hearing loss notably influences binaural benefit in sentence perception and that the Gap and Overlap maps provided the most significant benefit across hearing configurations, but the amount of benefit is relatively consistent across SNRs.

We analyzed data from the bimodal condition using a two-way ANOVA with two repeated independent factors, residual hearing and frequency map, at each SNR. Analyses showed that an increase in residual hearing significantly improved sentence perception scores. Frequency maps also demonstrated significant effects on mean percent scores. Results demonstrated that at -6 dB SNR, the FO map provided higher sentence perception when compared to Meet and Gap maps for users with less than 250 Hz of residual hearing. Sentence perception scores are not significantly different across the four frequency maps for bimodal users with residual hearing thresholds up to 500 Hz and 750 Hz. The analyses indicated that there is no significant interaction between residual hearing and frequency maps. However, there were significant effects of both residual hearing and frequency map on mean percent scores for 0 dB SNR, Quiet, and +6 dB SNR conditions. Thus, the map that may be recommended for each bimodal user depends upon their degree of residual hearing and the signal-to-noise ratio used.

We also performed two-way ANOVA analyses of data from the EAS condition using the two repeated independent factors, residual hearing and frequency map, at four different SNRs. At -6 dB SNR and 0 dB SNR, results demonstrated a significant improvement in sentence perception scores with better residual hearing. The analyses for these signal-to-noise ratios also revealed that the frequency map significantly influenced mean percent scores. Perception scores were not significantly influenced by different maps in the quiet or +6 dB SNR conditions. Therefore, the map that may be recommended for each EAS user depends upon their degree of residual hearing and the signal-to-noise ratio used.

In addition to determining the effect of frequency maps on sentence perception across SNRs, this study also sought to determine whether binaural benefit depends on frequency maps and which hearing technology provides higher benefit. At A250 Hz, the statistical analyses displayed no significant effects of hearing technology on sentence perception regardless of SNR and marginal differences in binaural benefit between the two hearing technologies across the frequency map at each SNR that were not statistically significant. This suggests that any map could provide similar binaural benefit for either bimodal or EAS users with useful residual hearing up to 250 Hz, regardless of the levels of background noise. At A500 Hz, overall EAS benefit is greater than bimodal benefit and any map excluding +6 dB SNR for the Gap map could provide similar binaural benefit for either bimodal or EAS users have useful residual hearing up to 500 Hz, regardless of the levels of background noise. At A750 Hz, differences in binaural benefit between bimodal and EAS devices were observed across the frequency map at each SNR. Analyses showed no significant effects of hearing technology on sentence perception at 0 dB SNR, +6 dB, SNR and in quiet conditions but significant effects at -6 dB SNR. Overall, bimodal benefit at A750 is relatively greater than EAS benefit.

Limitations

While the use of subjects with normal hearing aids the recruitment process and allows us to control for extraneous factors, such as duration of device use and hearing thresholds, our NH listener subjects were at an immediate disadvantage as they were acutely tested with different bimodal and EAS test maps. This provides an unfamiliar environment, as this configuration does not characterize their everyday bilateral listening experience, and, in essence, changes how their auditory system processes spectral and temporal cues for speech recognition. Our participants were tested for each frequency map with 20-minute familiarization, but without a habituation period among the maps. Our basis for acute testing is that there is no significant difference between acute and chronic conditions in bimodal patients (Gifford et al., 2017). Of course, further investigation is required to thoroughly investigate the effect of listening experience as data for just five subjects is not sufficient to draw definitive conclusions about the effect of listening experience.

Discussion

This study examined the effects of frequency maps on sentence perception in simulated bimodal and EAS listening conditions to determine the most effective map for three common residual hearing thresholds (A250 Hz, A500 Hz, A750 Hz) at four different signal-to-noise ratios (-6 dB, 0 dB, Quiet, 6 dB). In addition, binaural benefit was compared between the two technologies at each threshold and signal-to-noise ratio to determine whether binaural benefit depends on frequency maps and which hearing technology provides higher benefit. Results indicate that both the degree of residual hearing loss and the frequency map used notably influence binaural benefit in sentence perception. Gap and Overlap maps provide the most significant benefit across hearing configurations, but this is not consistent with all cases. Ideal maps are dependent upon signal-to-noise ratio, residual hearing thresholds, and the type of binaural device selected. Thus, each of these factors should be considered during the selection frequency maps for bimodal and EAS patients and treatment should be provided on a case-by-case basis.

Analyses of sentence perception scores from the bimodal hearing condition showed that at -6 dB SNR, 0 dB SNR, Quiet, and +6 dB SNR, both residual hearing thresholds and frequency maps impact sentence perception; however, interactions between the two factors were only significant at 0 dB, Quiet, and +6 dB signal-to-noise ratios. At -6 dB SNR, no significant interaction between residual hearing and frequency maps was observed. At -6 dB SNR, FO map can be recommended for A250 and A750 Hz, whereas either FO or Meet can be recommended for A500 Hz. At 0 dB SNR, any map can be recommended for A250 Hz, while NO or Meet can be recommended at A500 Hz and A750 Hz. At +6 dB SNR, any map can be recommended for A250 Hz and NO, Meet, or Gap can be recommended for A500 Hz. NO can be recommended for A750 Hz. In Quiet, Meet can be recommended at A250 Hz, Gap can be recommended at A500 Hz, and any map can be recommended at A750 Hz. One recent study claims that Full Overlap (FO) mapping provides optimal listening performance for bimodal listening situations, as results demonstrated a trend of increased sentence recognition scores paired with decreased perceived difficulty as overlap between electric and acoustic frequencies increased (Gifford et al., 2017). Although our results suggest that some conditions warrant the recommendation of FO map, these findings are mostly inconsistent with our conclusions; however, it should be noted that Gifford and colleagues also used implant recipients as subjects. Therefore, the impact of these thresholds on frequency maps could not be considered. It is likely that an experimental design aspect such as this factor is the cause of the discrepancy between the two data sets. However, other literature supports our findings. The results of another study suggest a significant decrement in performance with all overlap maps with background noise present and sentence perception results for each map that are dependent upon signal-to-noise ratio (Karsten et al., 2013). This is consistent with our findings. All studies agree that default map settings is not ideal for every case and that fittings should be individualized to optimize bimodal benefit.

Analyses of mean percent scores from the EAS hearing condition suggested that both residual hearing thresholds and frequency maps impact sentence perception at each signal-to-noise ratio, but that there is only significant interaction between residual hearing thresholds and frequency maps at -6 dB SNR, 0 dB SNR, and 6 dB SNR. At -6 dB SNR, any map can be recommended for A250 Hz, NO can be recommended for A500 Hz, and Gap can be recommended for A750 Hz. At 0 dB SNR, any map can be recommended for A250 Hz, NO can be recommended for A500 Hz, and Gap can be recommended for A750 Hz. At both +6 dB and Quiet signal-to-noise ratios, Gap can be recommended for A250 and A500 Hz, and any map can be recommended for A750 Hz. These findings are relatively consistent with previous EAS studies, as the majority concluded that the Gap map provided the higher benefit and was preferred by most listeners (Dorman & Gifford, 2010; Roland, Gantz, Waltzman, & Parkinson, 2016). Our data suggest that the Gap map is, in fact, ideal for most EAS hearing thresholds and signal-to-noise ratios, but there are some circumstances in which Gap is not the best option, such as the A250 Hz residual hearing threshold at all SNRs, where there is no statistical difference between the different maps, and the A500 Hz residual hearing threshold at -6 dB SNR and 0 dB SNR where NO map should be recommended. The differences between conclusions from previous studies and our own likely emanate from differences in experimental design. While our study used simulated bimodal and EAS conditions with normal hearing subjects, previous studies tested subjects with hearing loss who use bimodal and EAS devices in their daily lives. While the subjects used in these studies were more experienced in binaural listening than our NH subjects, individuals with hearing loss exhibit various degrees of residual hearing so that the impact of residual hearing on frequency maps could not be evaluated. However, it has been determined that the degree of residual hearing in the HA ear does affect functional hearing significantly (Dorman & Gifford, 2017; Dubno, Dirks, & Langhofer, 1982; Reiss, Eggleston, Walker, & Oh, 2016; Zhang, Heinz, Bruce, & Carney, 2001). Our study, which used simulated thresholds to control for this variable revealed that it is clinically important to differentiate the effects of hearing thresholds because there are some circumstances in which the typically used Gap map is not the most beneficial setting. These findings are consistent with existing literature, which suggests that the degree of residual hearing in the HA ear and signal-to-noise ratio can both impact speech perception (Dorman & Gifford, 2017; Dubno, Dirks, & Langhofer, 1982; Reiss, Eggleston, Walker, & Oh, 2016; Zhang, Heinz, Bruce, & Carney, 2001).

We performed statistical analyses of results from both bimodal and EAS simulations to compare the effects of residual hearing on frequency map selection between the two technologies. At A250 Hz, there were no significant effects of either frequency map or hearing technology on sentence perception, regardless of SNR. Marginal differences in percent scores between the two hearing technologies across the frequency map at each SNR were recorded; however, these differences are not statistically significant. At A500 Hz, EAS technology appeared to provide higher sentence perception over the four maps at each SNR. The statistical analyses showed no significant effects of either frequency map or hearing technology on sentence perception at -6 dB and 0 dB SNRs but revealed significant effects at two higher SNRs. These results suggest that different maps could provide higher sentence perception in relatively quiet environments among bimodal and EAS users who have up to 500 Hz of useful residual hearing. At A750 Hz, statistical analyses revealed no statistically significant effects of frequency maps or hearing technology on sentence perception regardless of SNR.

Lastly, we compared the effects of frequency maps on binaural benefit between bimodal and EAS technologies. Our analyses revealed that any map can provide similar binaural benefit for bimodal or EAS users with useful residual hearing up to 250 Hz, regardless of background noise levels. Most maps provide similar binaural benefit for bimodal or EAS users who have useful residual hearing up to 500 Hz, regardless of the levels of background noise, except for +6 dB SNR with the Gap map which indicated a slight preference for EAS technology. Any map can provide similar binaural benefit for bimodal or EAS users with useful residual hearing up to 750 Hz, regardless of background noise levels except -6 dB SNR with the Meet map which favors bimodal technology. Existing literature that compares the effectiveness of bimodal and EAS technologies is consistent with these findings; both binaural technologies provide similar benefit for users in most settings. Differences between bimodal and EAS technology benefit are minimal but are dependent upon residual hearing thresholds and signal-to-noise ratio.

Based on this study, we can conclude that current mapping strategies for bimodal and EAS devices are not as effective as they could be. While the Narrow Overlap map that is currently the default program on commercially available CI interfaces is certainly the best map in some cases, it is not the most beneficial map in all scenarios. In order to optimize bimodal and EAS benefit, audiologists should not simply default to the programmed maps, but should consider patients’ residual hearing, signal-to-noise ratio, and the type of binaural device used in order to select the most effective map for each case.

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