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Objective and subjective evaluation of wind noise reduction in digital hearing aids

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Objective and Subjective Evaluation of Wind Noise Reduction in Digital Hearing Aids

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Dedications

To my parents for their continuous love and support. To all of my friends and family who

think I'm smarter than I am. To Michael for listening to me complain and solving all of

my technical issues. To Roland for providing me with a healthy amount of distraction.

Acknowledgements

Table of Contents

List of Tables

List of Figures

Abstract

      Wind noise is problematic for hearing aid users who enjoy outdoor activities. Not only is it annoying, it can create distortion by overloading the microphone and masking signals that hearing aid users desire to hear. Some hearing aid manufacturers offer wind noise reduction in addition to general noise reduction (WNR + NR) for clinicians to manipulate in their software. This study compares objective and subjective measures of wind noise reduction as well as subjective measure of intelligibility obtained using various hearing aid manufacturers and noise reduction settings while HINT sentences were played in the presence of constantly generated wind. Significant differences in the subjective and objective amount of noise present and perceived speech intelligibility was found both between manufacturers and between noise reduction settings for each manufacturer. Subjectively, intelligibility and noisiness were positively correlated ($r=0.74$, $p>.001$); conditions that were perceived to be the most intelligible were the same conditions that were perceived to be the noisiest. The perception of intelligibility and noisiness depended on the interaction of hearing aid manufacturer and noise reduction setting ($p<.001$, effect size=.77) for hearing aids with WN + NR and depended on both hearing aid manufacturer ($p<.001$, effect size=0.67) and noise reduction setting ($p<.001$, effect size=0.61) individually for hearing aids with only NR. Objective measures of gain reduction were negatively correlated with perceived noisiness ($r=-0.87$ to 0.92 - depending on frequency range, $p>.001$) of sentences; as the amount of gain reduction decreased, the perceived noisiness increased. In this study, the amount of noise perceived to be present and the intelligibility of speech depended on both hearing aid manufacturer and how noise reduction was programmed. The perception of noisiness and intelligibility were positively correlated, suggesting that when more gain reduction was applied

sentences became less intelligible. Interestingly, for hearing aid manufacturers with NR only the perceived noisiness and intelligibility of sentences both increased when less noise reduction was applied. The results of this study have clinical implications for programming noise reduction settings in hearing aids when both wind and speech are present.

Introduction

Wind noise is a problem for most hearing aid users who enjoy outdoor activities. Not only is it annoying to listen to, it can create distortion by overloading the microphone and masks signals that hearing aid users desires to hear. Wind noise can be reduced through acoustic means and, when the microphone is not overloaded, through signal processing. Despite hearing aid manufacturers attempts to alleviate the problems associated with wind noise, Kochkin (2005), in one of the largest studies of hearing aid user's satisfaction, found only 49% of hearing aid users were satisfied with their hearing aids performance in wind. To address this issue, certain hearing aid manufacturers have recently added wind noise control features that clinicians can manipulate, similar to noise reduction (NR) features, within their software programming of the aids. More commonly, manufacturers have algorithms built in to the hearing aid processing that will reduce wind noise, but it may not be accessible to the clinician for manipulating the amount of wind noise reduction. At present, published data on WNR algorithms used by different hearing aid manufactures is lacking. The purpose of this study is to determine the efficacy of noise reduction algorithms used by different manufacturers to reduce wind noise while maintaining speech intelligibility.

Wind Noise and Hearing Aids

Wind noise is caused by turbulent air flow; that is, the large changes in particle velocity that arises when air collides with any object, such as the pinna, tragus, or a hearing aid. Turbulent air flow results in eddies, or random currents that are characterized by large spatial pressure differentials as opposed to laminar, or smooth, air flow that is characterized by air flowing in distinct layers with no air being exchanged between

layers. The sound pressure level resulting from wind increases dramatically with increasing wind velocity; that is, wind noise and wind velocity are positively correlated with one another (Strasberg, 1988). Specific to hearing aid users, the amount of wind noise they will experience is affected by many hearing aid related factors including but not limited to hearing aid style, microphone location relative to the wind source, microphone directionality, frequency response, and signal processing algorithms (Chung, Mongeau, & McKibben, 2009).

Turbulence occurs from disruptions in the path of air flow; therefore, bigger objects and more disruptions in the air path will generally result in more turbulence and, consequently, more wind noise. Dillon, Roe, and Katch, found that, in general, in-the-ear (ITE) hearing aids result in the least amount of turbulent air flow followed by completely-in-the-canal (CIC) hearing aids, with behind-the-ear (BTE) hearing aids resulting in the greatest amount of turbulent air flow (as cited in Thompson, 2002, p 82-83). In-the-ear hearing aids fully occlude the concha, thereby eliminating what would be an additional source of turbulent air flow, while also providing a smooth surface for laminar air flow. Completely-in-the-canal hearing aids also eliminate most of the turbulence that would occur at the concha, but lack the smooth surface of ITE hearing aids. Finally, BTE hearing aids rest in an area of high turbulence behind the pinna and are attached to an ear hook and tubing, which create additional sources of turbulence, resulting in greater wind noise. Due to other hearing aid factors, such as microphone openings, variable amounts of wind noise may be found within any one hearing aid style (Grenner, Abrahamsson, Jernberg, Lindblad, 2000).

The sound pressure level (SPL) resulting from turbulent air flow varies with the direction of the hearing aid microphone relative to the wind noise. Dillon et al (cited in Kates, 2008, p. 155-156) measured the SPL of wind noise arising over a range of 180 degrees relative to ITE, CIC, and BTE hearing aids fit to KEMARs right ear and concluded that the greatest SPL results from wind arising from 0 degrees azimuth while the least amount of SPL results from wind arising ipsilateral to the hearing aid ear, with a varying amount of SPL occurring from directions between the two extremes. Greater wind noise (SPL) was measured from wind arising contralateral to the hearing aid ear than from wind arising ipsilateral to the hearing aid ear. This is rationalized in that air flow arising ipsilateral to the hearing aid is likely still laminar upon coinciding with the hearing aid, whereas air flow arising contralateral to the hearing aid has already been disturbed when it reaches the hearing aid and is therefore more turbulent. For BTE hearing aids, the difference in SPL occurring at 0 degrees compared to 45 degrees is marginal, whereas a decrease in wind flow velocity is seen at 90 degrees (Chung, Mongeau, & McKibben, 2009).

As a direct consequence of the lack of correlation of wind noise at either microphone as well as the low frequency boost that is inherent to directional microphone arrays, omnidirectional microphones generally result in less wind noise than directional microphones (Chung, et al 2009; Chung, McKibben, & Mongeau, 2010). Directional microphones can increase the signal to noise ratio (SNR) when the signal of interest and noise are spatially correlated, but separated. For cancellation to occur the signal reaching the diaphragm from each microphone port must be correlated; otherwise addition or subtraction of the signals at either port may result in amplification of the signal rather

than reduction of the signal (Kates, 2008). In the case of wind, the noise will be spatially uncorrelated at each microphone and will therefore often result in larger, rather than smaller, vibrations of the microphone diaphragm. In addition, directional microphones have an inherent low frequency roll off secondary to the readily matching phase angles of low frequency wavelengths. To compensate for the low frequency roll off that is inherent to directional microphone arrays, directional microphones utilize a low frequency boost. The spectrum of wind noise is predominantly in the low frequencies, at around 300 Hz or less depending on wind velocity, with a steep roll off at higher frequencies (Wuttke, 1991; Larrson & Olsson, 2004). By nature of the spectrum of wind noise, the low frequency boost in directional microphone arrays is counterproductive to wind noise, making directional microphone arrays more susceptible to intolerable wind noise than omnidirectional microphones. Some hearing aids utilize an algorithm in which the hearing aid will automatically switch to omnidirectional mode upon detection of wind. In hearing aids that do not automatically switch, a hearing aid user should be counseled to switch his or her hearing aid to omnidirectional mode in the presence of wind.

Reducing Wind Noise in Hearing Aids

Acoustic means to reduce wind noise, such as a physical wind screen, is an effective way to reduce wind noise. Unfortunately, due to the small size of hearing aids a wind screen is unrealistic and therefore hearing aid manufacturers must rely on signal processing algorithms to reduce wind noise. To be effective, signal processing algorithms require a way for the hearing aid to separate wind noise from desired signals.

One of the most consistent distinguishing characteristics of wind noise is that it is predominantly low frequency in nature. When characterizing wind noise, despite small

differences in exact numbers, the general consensus is that it is strongly low frequency in nature with a relatively steep roll off above ~300 Hz (Wuttke, 1991; Dillon et al 1999; Larrson & Olsson, 2004, as reported in Kates, 2008, p 158-159). A spectrum algorithm that determines the presence or absence of wind based on the percentage of the incoming signal that is low frequency is one algorithm that can be used to reduce wind noise. Such an algorithm monitors the amount of the incoming signal that is low frequency to determine the presence or absence of wind. The algorithm then frequency shapes, or decreases the amount of gain at low frequencies, when wind is indicated (Kates, 2008).

Unlike speech, wind is highly uncorrelated at any point in time. Consequently, another algorithm that can successfully be used to reduce wind noise is a correlation algorithm. Correlation algorithms utilize a statistic that determines the correlation of incoming signals at the front and rear microphones. Therefore, dual microphones are a requirement for a hearing aid to utilize this algorithm. Wind lacks the spatial correlation that other signals, such as speech and external background noise, will have at both microphones; whereas speech will be spatially correlated at each microphone, wind will be uncorrelated. When the statistic determines the signal is uncorrelated at each microphone, this is indicative of wind and the gain will be reduced. Correlation algorithms can be done in the frequency domain using Fast Fourier Transform (FFT), whereby the amount of correlation is determined in several individual frequency bins. Gain would then be set in each frequency bin depending on the amount of correlation in each frequency bin (Kates, 2008).

In addition to an algorithm to reduce wind noise, some hearing aid manufacturer's offer wind noise control features in their programming software that clinicians can

manipulate similar to noise reduction (NR). More commonly, manufacturers have general noise reduction that will likely reduce wind noise, but is not monitoring for wind noise specifically. At present, published data on wind noise reduction algorithms used by different hearing aid manufactures is lacking. The purpose of this study is to determine the efficacy of algorithms used by different manufacturers in reducing wind noise while maintaining speech intelligibility. Specifically, the following questions will be addressed: 1) Are there consistent subjective differences, both within and between listeners, in speech intelligibility within and across manufacturers? 2) Are there subjective differences in perceived noisiness within and across manufacturers? 3) Do subjective measures of noisiness correlate with objective measures of gain reduction within and across manufacturers?

Hearing instruments from four manufacturers were chosen for this study. The hearing aid chosen from manufacturer A utilizes 16 channels and two microphones, one for omnidirectional processing and one for directional processing, which are used independently of one another. A fast-acting, single-microphone noise reduction algorithm is utilized to reduce noise between the syllables of speech and maintain appropriate gain prescription when speech is present. Incoming signals are analyzed and the most appropriate algorithms are implemented depending on overall input level, input level in each channel, statistical categorization of inputs and the signal-to-noise ratio present in each channel. The clinician can manipulate how much gain reduction will be applied given several different noise categories, one of which is wind. The turbulence of wind passing across the microphone diaphragm triggers the wind noise reduction algorithm.

The resulting adaptation is a level dependant decrease in output for the four lowest hearing aid channels (Manufacturer A, personal communication, October 20, 2010).

The hearing aid chosen from manufacturer B utilizes 20 channels and dual omni-directional microphones. The amount of gain prescription and noise reduction applied in each channel depends on the incoming signal, which is classified into one of 4 categories. For each of the categories, the clinician can manipulate the amount of noise reduction and wind noise reduction that takes place. The noise reduction algorithm is level dependant and gain reduction is applied in the bands where noise is the dominant signal, whereas additional gain is provided in the bands where speech is the dominant signal (Manufacturer B, personal communication, November 3, 2010).

The hearing aid chosen from manufacturer C utilizes channel free, fast acting processing which continuously adjusts the gain of the hearing instrument to amplify each phoneme individually without dividing the signal into fixed channels. When speech and noise are detected, the hearing aid uses adaptive directionality in combination with adaptive noise reduction to achieve the best signal to noise ratio and increase comfort, respectively. Depending on the environment, adaptive directionality transitions between high-frequency directional with null steering above 1000 Hz and full directional with null steering in all bands. The noise reduction system functions in independent bands across the frequency range to reduce noise and maintain speech. The noise reduction system has three modes: a speech mode which prevents noise reduction when speech is detected, a comfort mode which initializes more noise reduction given the input level of noise detected, and a wind noise mode which utilizes a "fixed reduction for all bands which is important when outdoors". According to Manufacturer C (personal communication,

November 1, 2010) the hearing aid utilizes a correlation algorithm to determine if wind noise is present and, if wind is detected, the directionality system will automatically fade into high-frequency directionality mode and noise reduction is applied across the frequency range.

The hearing aid chosen from manufacturer D utilizes 10 channels and reduces noise on a per channel basis depending on the modulation characteristics of the signal present in each channel. Simultaneously, the high frequency region is monitored for the presence of harmonically related signals, which suggests the presence of speech and prevents excessive noise reduction in those channels when harmonically related signals are present. Multi-band adaptive directionality is used in four individual frequency bands, depending on the input in each of the four frequency bands directionality in each band will switch independently between full-directional, omnidirectional and split-directional mode to achieve the best signal to noise ratio in each of the bands. In the instant of wind noise, this hearing aid responds by applying level dependant noise reduction and automatic microphone switching based on the amount of signal present that would benefit from directionality. For example, if wind noise is excessive and speech signals are not present, directionality would not be activated; however, if wind noise is modest and speech signals are present that would benefit from directionality the hearing aid would go into split directional mode keeping the low frequency bands in omnidirectional mode and the high frequency bands in directional mode (Manufacturer D, personal communication, September 17, 2010).

Methods

Participants

A total of 20 participants, nine male and eleven female, were recruited for this study. Participants ranged in age from 22-34 with a mean age of 26. All participants had normal hearing and normal middle ear status, which was confirmed with pure-tone audiometry and tympanometry, respectively. Hearing thresholds of 20 dB HL or better from .5-8 kHz and normal Type A pressure-compliance functions were required, bilaterally.

Signal Preparation

Hearing Aids

Four commercially available behind-the-ear (BTE) style hearing aids were used in this study. Hearing aids were programmed using the manufacturer's software. Each hearing aid was programmed to fit a flat 65 dB sensorineural hearing loss using the manufacturer's default prescription for gain. A moderately-severe flat hearing loss configuration was chosen to ensure sufficient gain at all frequencies to activate level dependant noise and wind noise reduction algorithms. Hearing aids were coupled to an unvented earmold via standard size 13 tubing* and fit to KEMAR's right ear. An unvented earmold was selected to maintain a flat frequency response. Noise reduction and, where applicable, wind noise reduction, was programmed in several different ways for each hearing aid which resulted in a total of 12 conditions as shown in Table 1. All other hearing aid features were programmed as similarly as possible for each manufacturer, the details of which can be found in Appendix A.

Hearing Aid A and Hearing Aid B both have wind noise reduction available in their software for clinicians to manipulate in addition to general noise reduction. Wind noise reduction can be set to a minimum, moderate, or maximum amount, similar to how noise reduction can be applied in most hearing aid software. Hearing aid A uses two microphones, one for omni-directional processing and one for directional processing. The turbulence of wind across the microphone triggers the wind noise algorithm so, in theory, noise alone which is not turbulent should not trigger the wind noise algorithm. When turbulence is picked up at the microphone, the resulting adaptation is a level dependant decrease in output level for the four lowest hearing aid channels. Hearing aid B does not differentiate between different types of noise, but reduces noise on a per channel basis in bands where noise is the dominant signal (Manufacturer B, personal communication, November 3, 2010). Therefore in the case of wind, which is low frequency in nature, gain reduction would be applied in low frequency channels.

Hearing aid C and D both have general noise reduction, rather than noise reduction and wind noise reduction, available in their software for clinicians to manipulate. Hearing aid C utilizes a correlation algorithm to determine if wind is present. When the incoming signal is uncorrelated, microphone switching and gain reduction takes place. The directionality system automatically switches to high frequency directionality mode and noise reduction results in a level-dependant fixed gain reduction of at least 10 dB takes place (Manufacturer C, personal communication, November 3, 2010). Hearing aid D also uses a correlation algorithm to determine if wind is present and utilizes directional microphone switching when wind noise is likely present. Directional

microphone switching is tied to the amount of wind detected as well as how much of the

input signal would benefit from having a directional array. When a threshold amount of

wind is detected, the hearing aid will either go into a split-directional or omnidirectional

array depending on the amount of the input signal that is present in addition to

uncorrelated wind that could benefit from a directional array. If the hearing aid goes into

a split-directional array, channels 1000 Hz and below are processed in omnidirectional

while higher frequency stimuli are processed in a directional array (Manufacturer D,

personal communication, September 17, 2010).

*with the exception of hearing aid D which was a RITE coupled to putty, which acted as

an unvented earmold

Table 1 Variable programming of Wind Noise and Noise Reduction in the four hearing
aids used in this study resulted in 12 unique conditions. Hearing aid A and B resulted in 4
conditions each: wind noise and noise reduction on maximum settings, wind noise at
maximum setting and noise reduction at minimum setting, wind noise at minimum setting
and noise reduction at maximum setting, and wind noise and noise reduction at minimum
setting. Hearing aids C and D resulted in 2 conditions each: noise reduction at maximum
setting and noise reduction at minimum setting.

	Conditions					
Manufacturer	WN on/ NR on	WN on/ NR off	WN off/ NR on	WN off/ NR off	NR on	NR off
A	X	X	X	X		
B	X	X	X	X		
C					X	X
D					X	X

Stimuli Preparation

A table fan (feature comforts, model #0118251) was used to generate wind. The

fan was placed 91 cm from KEMAR at 45 degrees azimuth to the right. The fan speed

was set to high and, using a La Crosse Technology EA-3010U handheld Anemometer,

the wind speed at the top of KEMAR's pinna, or the location of the behind-the-ear

microphones, was ~5 mph. A Tannoy System 600 speaker was used to generate speech.

The speaker was placed 91 cm from KEMAR at 0 degrees azimuth. Sentences from list 1

of the Hearing In Noise Test (HINT) were routed from a GSI 16 audiometer, calibrated

July 2009, to the speaker at a level of 65 dB HL. HINT sentences were calibrated using

the 1 kHz calibration tone on the HINT compact disk. The SPL of the HINT sentences

were also measured with a Larson Davis System 824 precision SLM. In a 305cm x

305cm double-walled IAC sound treated booth, wind was presented from the fan at a

speed of   ~ 5 mph for two minutes for each condition to allow ample time for noise

reduction in each of the conditions to fully engage. After two minutes, HINT sentences

were played from the speaker at a level of 65 dB SPL in conjunction with continuous fan

generated wind. Output of the 12 hearing aid conditions in response to the sentences in

wind were recorded through an ER-11 preamplifier with a 1/2" microphone coupled to a

Zwislocki coupler mounted to KEMAR.   Output of the 12 conditions were recorded to

the hard drive of a personal computer, to be analyzed offline, using commercial sound

editing software (Cool Edit Pro 2.1).

Two, of the ten total recorded, HINT sentences from list 1 were chosen at random

to use for subjective and objective analysis of wind noise reduction across the different

conditions. These two sentences were "the woman helped her husband" and "the player

lost his shoe". The average RMS of each sentence, with approximately 1 second of wind

only before and after each sentence, was equalized for each condition. The average RMS

was equalized to prevent audibility of the sentences from being a confounding factor,

since it is known that all hearing aids do not provide the same amount of gain.

Procedure

A commercially available signal presentation program (SuperLab version 4.0) was used to create an experiment for participants to make judgments on intelligibility and noisiness of a HINT sentence processed through the 12 conditions. Participants were first asked to judge intelligibility and then asked to judge noisiness of the same HINT sentence. The sentence that each participant heard was randomly chosen from the two recorded sentences. Ultimately, 10 Participants heard "the wife helped her husband" and 10 participants heard "the player lost his shoe". For intelligibility, a paired comparison forced-choice paradigm experiment was created in which each participant heard the same HINT sentence processed in two different conditions and was asked to choose the most intelligible condition of the pair. Participants did this for all 66 possible pairs of the 12 conditions. For noisiness, participants heard the same HINT sentence processed in each condition individually and was asked to rate the nosiness of each of the conditions on an analog scale from 1 to 9, with 1 being the least noise and 9 being the most noisy. Participants were given the following typed instructions, which were also read aloud prior to beginning the study:

"The sentences you will be listening to have been recorded through a hearing aid while wind noise was present. At the beginning of each sentence you will hear some wind noise. The wind noise will sound different for each sentence because each sentence is being processed differently and through several different hearing aid manufacturers. For the first part of the study you will be presented with several pairs of sentences. You will be asked to choose the sentence that is the most intelligible. I want you to judge only intelligibility, meaning the sentence that is the clearest and the easiest to understand. I want you to choose the most intelligible sentence regardless of the amount of wind noise present. Sentences cannot be replayed; you will only be allowed to listen to each sentence once. For the second part of the study you will be asked to judge the noisiness of several sentences. You will be asked to rate the noisiness of the sentences on a scale of 1-9, 1 being not noisy at all and 9 being very noisy. Sentences cannot be replayed; you will only be allowed to listen to each sentence once. Before we begin you will do a practice trial.

Please let me know if the volume is too loud or too soft and it will be adjusted as needed before beginning the study."

For both intelligibility and noisiness the participants could not replay any of the conditions and had to make either a choice, for intelligibility, or a rating, for noisiness, before proceeding to the next pair of conditions (for intelligibility) or single condition (for noisiness). Participants had to press a key to signal they were ready to hear the next condition before it was played.

Data Analysis

Subjective Measurements

A custom software program written to compute the coefficient of agreement based on the formula by Kendall and Gibbons (1990) was used (Lincoln Gray, personal communication, October 2, 2010) to determine if there was a significant, consistent difference in intelligibility rankings of the 12 conditions within and between participants. All possible pairs of conditions (66) were presented to each participant. A coefficient of agreement evaluates consistency within and between participants by the number of circular triples committed by a participant. A circular triple occurs when a participant is inconsistent in their judgments. For example, if a participant is asked presented with 3 options: A, B, and C and the participant judges A superior to B and B superior to C, then by default A should be judged superior to C. However, in that case if C is judged to be superior to A, then a circular triple has occurred. A circular triple reflects inconsistency on the participant; therefore the less circular triples, the higher the z score from Kendall's statistical test, and more likely the participants rankings will be significantly different than chance. The coefficient of agreement program gives the number of circular triples and a z-score reflecting difference from chance for each individual participant and for the

group. Note that individuals can be completely consistent as individual observers, but very different comparing one to the other. The program also reports rankings of the conditions presented to participants and the total number of times each condition was chosen as the more intelligible of the pair.

Two separate MANOVAs were performed to determine the effect of hearing aid manufacturer and noise reduction settings on the perceived intelligibility and noisiness of conditions. One MANOVA was used to analyze data with the two hearing aid manufacturers who have wind noise reduction and noise reduction (WNR + NR); within-subjects factors were manufacturer (A or B), WNR on or off and NR on or off and between subjects factor was sentence, as 10 participants heard each sentence. The second MANOVA was used to analyze data with the two hearing aid manufacturers who only have noise reduction (NR) settings; within-subject factors were manufacturer (C or D), NR on or off and between subjects factor was again sentence.

Objective Measurements

Cool Edit Pro version 2.1 was used to make physical measures of the dB SPL output of the 12 recorded conditions. The investigator making the physical measurements was blinded to the conditions. Output was measured at 2 time periods for each condition, once before the HINT sentence began and wind only was present (noise only measure) and again when the sentence and wind were present (signal + noise measure). Output was measured at several different frequencies for both the noise and the signal + noise measurement of the recorded conditions: .25, .5, 1, 2, 4, and 6 kHz. The amount of frequency specific wind noise gain reduction (dB SPL) was calculated for each condition by subtracting the noise only output from the signal + noise output at each frequency

measured. Low, mid, and high frequency gain reduction was calculated by taking an average of the gain reduction at .25 and .5 kHz, 1 and 2 kHz, and 4 and 6 kHz, respectively.

Results

Intelligibility

An independent samples t-test comparing the number of circular triples committed by participants who heard sentence 1 and participants who heard sentence 2 yielded no significant difference (p>.05). The ranking of intelligibility, or preference, was highly correlated and significant (r=0.67, p=.005) between participants who heard sentence 1 and participants who heard sentence 2. Given no significant difference in circular triples and the significantly correlated ranking of intelligibility between the two sentence groups, all further results were obtained by analyzing data from all participants as a whole.

Intelligibility: All Conditions

Kendall's coefficient of agreement yielded significant differences (p<.001, effect size=16.6), both within and between participants, in the perceived intelligibility of the 12 conditions. Figure 1 demonstrates how subjects ranked intelligibility of the 12 conditions. (values can range from 11 to 0 if there were a single overall 'winner' and 'loser').
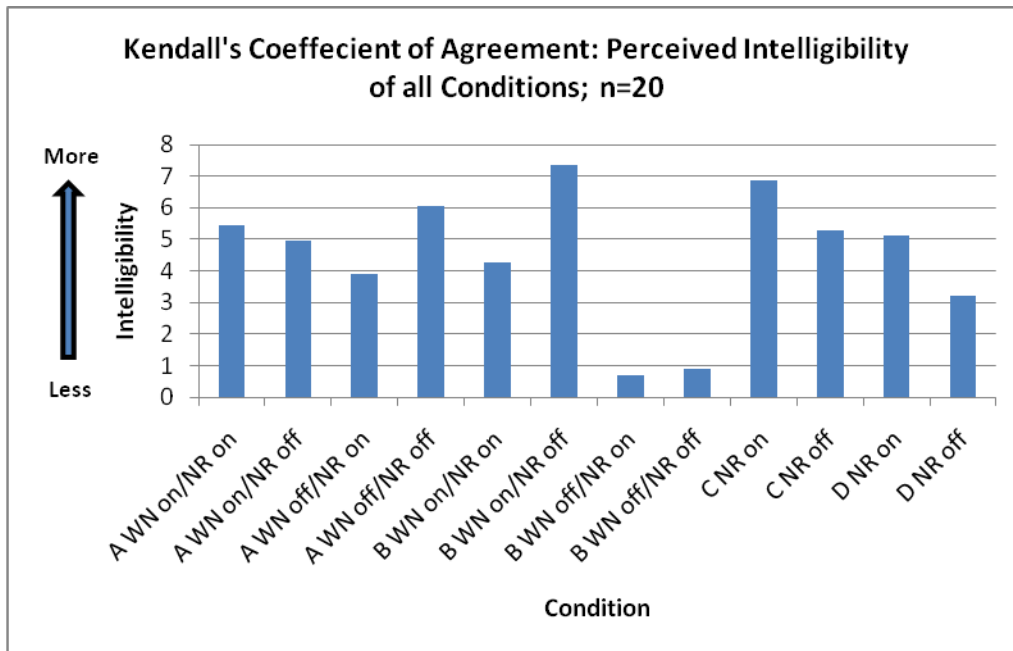
Figure 1 Ranking of intelligibility, or preference, of conditions among participants using Kendall's Coefficient of Agreement. Intelligibility given by the average total number of times each condition was chosen (n=20) to as most intelligible of the sentence pair, 0 being the least intelligible and 11 being the most intelligible on this scale. WN= wind noise setting; NR= noise reduction setting; on= set to maximum possible setting; off=set to minimum possible setting.

Intelligibility: Correlation with Nosiness

The perceived intelligibility of a condition was highly and significantly correlated with the perceived noisiness of the same condition (r=0.74, p>.001, r2=.5 or a medium effect size). Perceived intelligibility and noisiness were directly correlated; as the perceived intelligibility increased, the perceived noisiness increased. Figure 2 demonstrates the correlation between the subjective measures of intelligibility and noisiness when wind was present for all conditions.
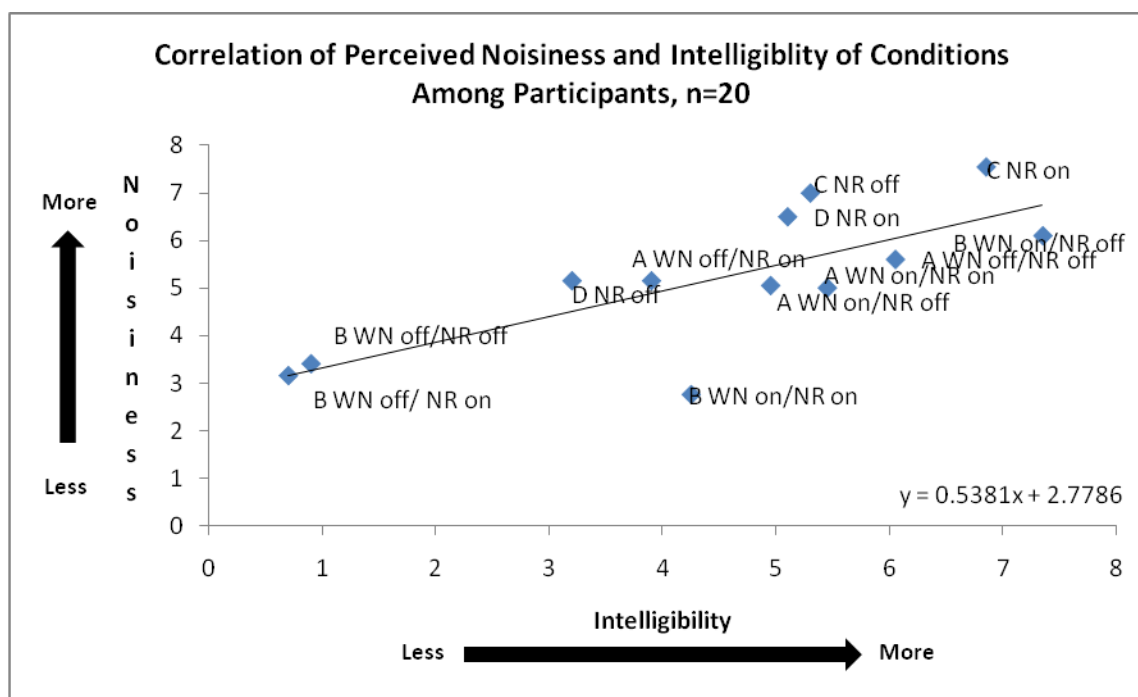
Figure 2 Correlation of intelligibility and noisiness of conditions. Perceived intelligibility and noisiness were positively related. Intelligibility given by the average total number of times each condition was chosen (n=20) as the most intelligible of the pair; 0 being the least intelligible and 11 being the most intelligible on this scale. Noisiness given by the average noisiness rating (on a scale of 1-9) given to each condition (n=20); 0 being the least noisy and 9 being the most noisy on this scale.

Intelligibility: Manufacturers with Wind Noise Reduction and Noise Reduction (A and B)

MANOVA yielded a significant interaction between hearing aid manufacturer and noise reduction setting on the perceived intelligibility of conditions involving hearing aid manufacturers with WNR + NR (p<.001, effect size=.77). The left side of figure 3 demonstrates the interaction of hearing aid manufacturer and noise reduction settings on the perceived intelligibility of the conditions. With the exception of wind noise reduction on and noise reduction off, hearing aid manufacturer A was perceived to be more intelligible than hearing aid manufacturer B for all noise reduction settings. When wind

noise reduction was on and noise reduction was off, manufacturer B was perceived to be more intelligible than manufacturer A.

Intelligibility: Manufacturers with Noise Reduction (C and D)

A MANOVA yielded significant main effects of hearing aid manufacturer ($p<.001$, effect size=0.67) and noise reduction setting ($p<.001$, effect size=0.61) on the perceived intelligibility of conditions involving hearing aid manufacturers with NR, but no interaction. The right side of figure 3 demonstrates the main effects of hearing aid manufacturer and noise reduction settings on the perceived intelligibility of the conditions. Regardless of noise reduction setting, manufacturer C was perceived to be more intelligible than manufacturer D. Regardless of manufacturer, conditions in which noise reduction was set to maximum (NR on) were perceived to be more intelligible than conditions in which noise reduction was set to minimum (NR off).
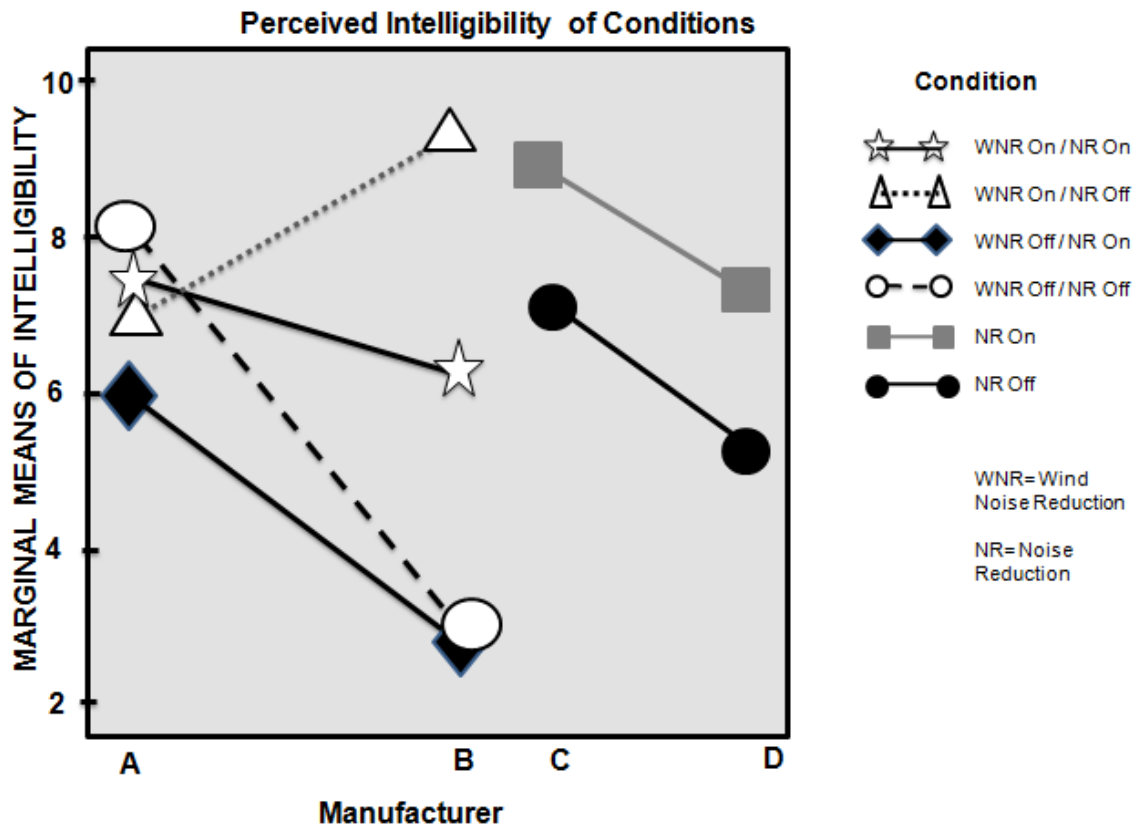
Figure 3 Perceived intelligibility of conditions. Intelligibility given by the average total number of times each condition was chosen (n=20) as the most intelligible of the pair; 2 being the least intelligible and 10 being the most intelligible on this scale. Between manufacturers with WNR + NR and manufacturers with NR only, conditions WN on/NR on and WN off/NR off are most comparable to NR on and NR off, respectively.

Noisiness

An independent samples t-test comparing the noisiness rating of the 12 conditions by the participants who heard HINT sentence 1 and participants who heard HINT sentence 2 yielded insignificance (p>.05). The numerical scale of noisiness rating, or noisiness, was highly correlated and significant (r= 0.82, p<.001) between participants who heard HINT sentence 1 and participants who heard HINT sentence 2. Given no significant difference in nosiness rating and the significantly correlated nosiness rating between the two sentence groups, all further results were obtained by analyzing data from all participants as a whole.

Noisiness Rating: Correlation with Objective Gain Reduction

The perceived noisiness of a condition was highly and significantly correlated with objective gain reduction. The correlation was negative, as expected, showing that louder sounds (more gain) are perceived as more noisy. This relationship was true for low frequency gain reduction ($r=-0.92$, $p>.001$), mid frequency gain reduction ($r=-0.92$, $p>.001$) and high frequency gain reduction ($r=-0.87$, $p>.001$). Gain reduction at low, mid, and high frequency regions differed in the absolute amount of gain reduction; the greatest amount of gain reduction was measured at high frequency regions and the least amount of gain reduction was measured at low frequency regions; as demonstrated in Figure 4 in the shift along the y-axis for low, mid, and high frequency regions and the amount of gain reduction.
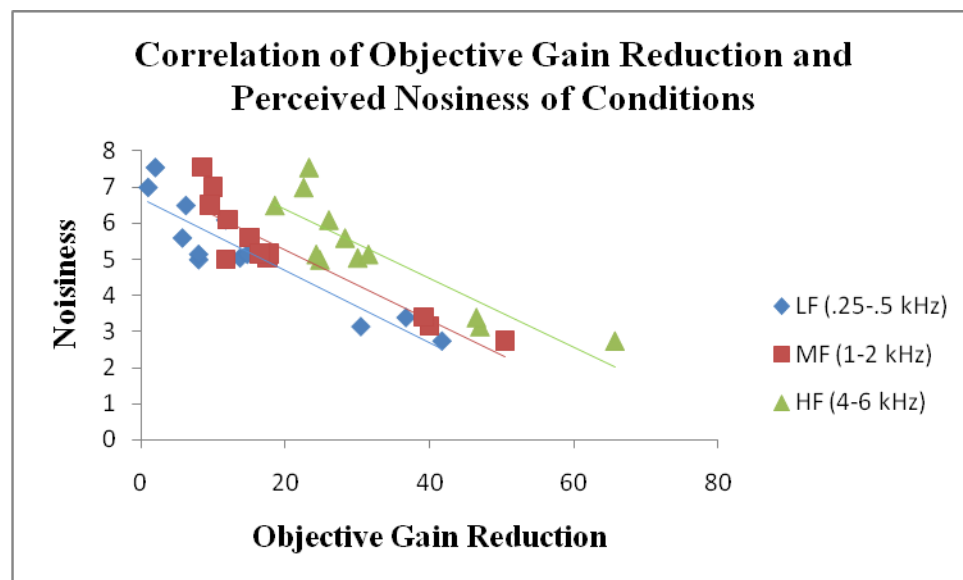

Figure 4 Correlation of perceived noisiness and objective gain reduction across low frequency, mid frequency, and high frequency regions for all conditions when wind was present. Noisiness given by the average noisiness rating (on a scale of 1-9) given to each condition (n=20); 0 being the least noisy and 8 being the most noisy on this scale.

Noisiness: Manufacturers with Wind Noise Reduction and Noise Reduction (A and B)

A MANOVA yielded a significant interaction between hearing aid manufacturer and noise reduction setting on the perceived noisiness of conditions involving hearing aid manufacturers with WNR + NR programming (p<.001, effect size=.77). Figure 5 demonstrates the interaction of hearing aid manufacturer and noise reduction setting on perceived noisiness of the conditions. With the exception of wind noise reduction on and noise reduction off, hearing aid manufacturer A was perceived to be noisier than hearing aid manufacturer B for all noise reduction settings. When wind noise reduction was on and noise reduction was off, manufacturer B was perceived to be noisier than manufacturer A.

Noisiness: Manufacturers with Noise Reduction (C and D)

A MANOVA yielded significant main effects of hearing aid manufacturer and noise reduction setting on the perceived noisiness of conditions involving hearing aid manufacturers with NR (p<.001, effect size=0.67, 0.61). Figure 5 demonstrates the main effects of hearing aid manufacturer and noise reduction settings on the perceived noisiness of the conditions. Regardless of noise reduction setting, manufacturer C was perceived to be noisier than manufacturer D. Regardless of manufacturer, conditions in which noise reduction was set to a maximum (NR on) were perceived to be noisier than conditions in which noise reduction was set to a minimum (NR off).
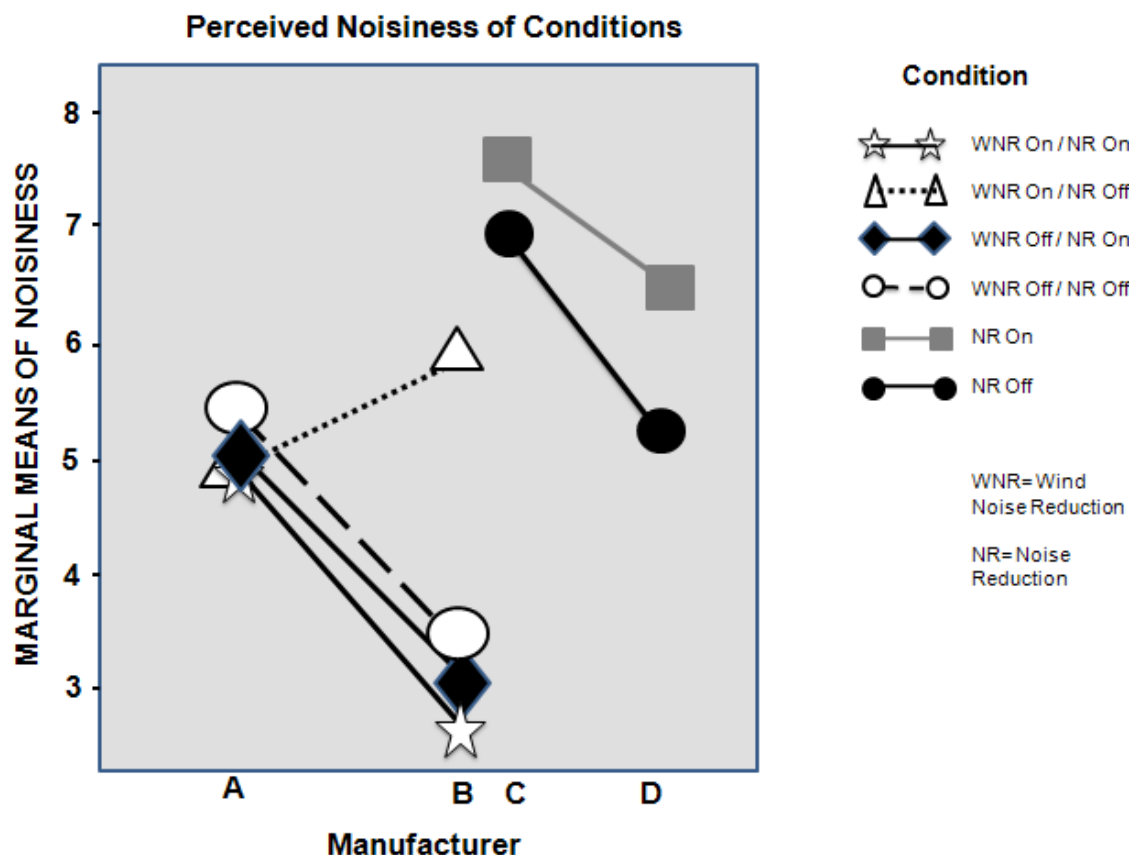
Perceived Noisiness of Conditions

Figure 5 Perceived noisiness of conditions. Noisiness given by the average noisiness rating (on a scale of 1-9) given to each condition (n=20); 3 being the least noisy and 8 being the most noisy on this scale. Between manufacturers with WNR + NR and manufacturers with NR only, conditions WN on/NR on and WN off/NR off are most comparable to NR on and NR off, respectively.

In summary, there were significant differences in the perceived intelligibility and noisiness rating of the 12 conditions and subjective measures of noisiness were significantly correlated with objective measures of gain reduction. Perceived intelligibility and noisiness depended on an interaction between manufacturer and noise reduction setting for hearing aids with both WNR + NR and depended on manufacturer and noise reduction settings individually for hearings aids with only NR.

Discussion

        Hearing aid users face turbulent wind that cannot be replicated in a laboratory, yet clinicians need data demonstrating the efficiency of noise and wind noise reduction algorithms in those conditions, particularly when speech is present. To date clinicians have to rely on manufacturer's information on how the hearing aids are designed to perform in wind but have no data available to support or refute their claims. Other studies have demonstrated the effects of different hearing aid styles, position of microphones, and directionality of microphones on the amount of wind noise, but have yet to analyze the efficiency of noise reduction algorithms at reducing wind noise in commercially available hearing aids (Chung et al, 2009; Chung et al, 2010; Kates, 2008; Thompson 2002). This study was designed from a clinical stand point to assess the efficiency of wind noise and noise reduction algorithms at reducing wind noise while maintaining speech intelligibility. Knowing that the turbulent conditions that hearing aid user's face cannot be duplicated, a fan was used to generate wind at a speed typical of a light breeze (Huler, 2004) while recorded speech was simultaneously played and the resulting sound quality from 4 hearing aid manufacturers, 2 with WNR + NR and 2 with NR only was evaluated.

Perceived Intelligibility in hearing aids with WN+NR and NR only

        There were significant differences in the perceived intelligibility of the 12 conditions evaluated in this study; however the differences yielded no consensus as to which hearing aid or noise reduction settings were more intelligible. How each of those factors contributed to the perceived intelligibility depended on whether or not the hearing aid had WNR + NR or NR only.

The perceived intelligibility of the two manufacturers with WNR + NR depended on complex interactions (no single the manufacturer nor wind noise or noise reduction setting were clearly better) whereas manufacturers with only NR had main effects of manufacturer and noise reduction. Two of the conditions in the hearing aids with WNR + NR (A and B), those conditions being when both wind noise reduction and noise reduction were set to maximum (WNR on/NR on) and when both were set to minimum (WNR off/NR off), were very similar to the conditions used in manufacturers with NR only (C and D), those conditions being noise reduction set to maximum (NR on) and minimum (NR off). As demonstrated in Figure 3, in those 4 extreme conditions hearing aids A and C were more intelligible than hearing aids B and D, respectively, regardless of noise reduction settings. As for noise reduction settings in the 4 extreme conditions, sentences were perceived to be more intelligible when those settings were at a minimum for manufacturer A, but were perceived to be more intelligible when those settings were at a maximum for hearing aids B, C and D.

Intelligibility increased in the extreme condition where noise reduction settings were programmed to maximum as compared to minimum for three of the four hearing aids used in this study. While the resulting favorable increase in intelligibility among the majority of the hearing aids used in this study are intuitive to what a clinician would predict with increased noise reduction, it is a finding that has yet to be consistently supported in the literature. Noise reduction has been shown to consistently increase comfort in noise, but not necessarily speech intelligibility (Zakis, Hau, & Blamey, 2009; Bentler, Wu, Kettel, Hurtig, 2008). The results of this study are not surprising, however, because the "noise" was wind alone. Wind noise theoretically triggers level dependant

gain reduction only in the lowest hearing aid channels, which should not degrade speech intelligibility. In addition, this study did not measure speech intelligibility objectively, but asked listener's to subjectively assess speech intelligibility. Chung, Tufts, and Nelson (2009) did demonstrate increased speech intelligibility as well as sound quality preference among listeners when modulation-based digital noise reduction was activated in the presence of other real-world noises, lending support to the results found here. However, this study is the first to analyze the effects of gain reduction on speech intelligibility in the presence of wind noise alone and should be replicated to determine if these results are potentially generalizable.

Perceived Noisiness of Speech in Hearing Aids with WNR + NR and NR only

The perceived noisiness of manufacturers with WNR +NR depended on the manufacturer as well as the wind noise and noise reduction settings whereas manufacturers with only NR had main effects of manufacturer and noise reduction setting. In the extreme conditions aforementioned for hearing aids with wind noise and noise reduction, however, there were main effects of hearing aid and noise reduction settings similar to the main effects seen for hearing aids with only NR. In those 4 extreme conditions hearing aids A and C were noisier than hearing aids B and D, respectively, irrespective of noise reduction settings. As for noise reduction settings in the 4 extreme conditions, sentences were perceived to be noisier when those settings were at a minimum for manufacturers with WNR + NR (A and B), but were perceived to be noisier when those settings were at a maximum for manufacturers with only NR (C and D). When not separating the two groups of manufacturers, but comparing the extreme conditions of all 4 manufacturers, manufacturers with WNR + NR (A and B) at maximum (WNR on/NR

on) were both less noisy than manufacturers with NR only (C and D) at maximum (NR on).

Objective measures of gain reduction were significantly, indirectly correlated with noisiness; with less objective gain reduction, the perceived noisiness of a condition increased. The most absolute gain reduction was measured at high frequency regions, which is also counter intuitive to what one would predict given that the hearing aids noise reduction algorithms are designed to reduce output only in the lowest frequency bands when wind is present in the absence of other noise. One possible explanation for greater absolute gain reduction measured in the high frequency regions than the low frequency regions is that the noise reduction algorithms are level dependant and, in the case of a flat hearing loss configuration, hearing aids gain prescription often provides more high frequency than low frequency amplification to maximize speech intelligibility.

Listener's perceived the sentences to be less noisy when noise reduction was set to maximum for hearing aids with WNR + NR, but perceived the sentences to be noisier when noise reduction was set at maximum for hearing aids with NR only. The results for hearing aids with WNR + NR are expected whereas the results for the aids with NR only are surprising, especially given that previous researchers have demonstrated positive effects of noise reduction, when activated, on the perceived comfort of sounds (Zakis, Hau, & Blamey, 2009). It is unclear as to why the hearing aids used in this study with WNR + NR were perceived to be less noisy when noise reduction was programmed at maximum and hearing aids with NR only were perceived to be more noisy when noise reduction was programmed at maximum. Although these results are surprising, the fact

that objective gain reduction was significantly, indirectly correlated with noisiness lends support to the reliability of the listener's subjective rating of noisiness.

When analyzing the perceived noisiness of sentences in wind for all 4 manufacturers in the extreme maximum setting, manufacturers with WNR + NR were both perceived to be less noisy than manufacturers with only NR. It is not surprising that, when the noise source is wind, manufacturers programmed with WNR + NR at maximum would be more efficient at reducing wind noise, compared to manufacturers with NR only at maximum. This is the first study to compare the noisiness of hearing aids with WNR + NR to hearing aids with only NR in the presence of wind. This study should be replicated and, ideally, other studies should be done to include different hearing aid manufacturers to determine if there is a trend in 1) manufacturers with NR only being perceived to be noisier when NR is set to maximum compared to minimum, 2) manufacturers with WNR + NR being perceived to be less noisy, when programmed at maximum, compared to manufacturers with NR only when the noise source is wind.

Noisiness and Intelligibility

Regardless of manufacturer or noise reduction setting, intelligibility and noisiness were positively correlated with one another indicating that what affects intelligibility also affects noisiness (see figure 2). In this study, sentences that were perceived to be the most intelligible were also perceived to be the noisiest and sentences that were perceived to be the least intelligible were also perceived to be the least noisy. It is likely that the majority of clinicians would increase the amount of wind noise and noise reduction in the case of a of a hearing aid user who complains of wind noise. This finding has clinical applications in that there may be a tradeoff between intelligibility and noisiness. The

results of this study suggest that appropriate programming not only depends on the manufacturer and that manufacturer's noise reduction settings, but also on whether a patient's primary complaint is loudness or speech intelligibility when speech and wind are simultaneously present.

Conclusion

Significant differences were found, with a large effect size, in the intelligibility of the 12 conditions implemented in this study. Noisiness was significantly, positively correlated with participants' preference for intelligibility; the conditions that the participants rated as noisiest were the same conditions that the participants ranked as most intelligible. In addition, objective, physical measures of gain reduction were significantly correlated with subjective measures of noisiness. Although there were significant differences in intelligibility and noisiness of the 12 conditions, there was no clear answer as to how manufacturers with wind noise reduction compare to manufacturers with only noise reduction. To further investigate the effects of manufacturer and noise reduction setting on speech intelligibility and noisiness it was necessary to separate manufacturers with WNR + NR and manufacturers with NR only. When analyzed separately there were clear interaction and main effects of manufacturer and noise reduction setting on hearing aids with WNR + NR and NR only, respectively. Again, there was not a single noise reduction setting or manufacturer that resulted in improved intelligibility or noisiness. This study indicates that extreme noise reduction settings may have adverse affects depending on whether the patient's primary complaint is understanding speech or the noisiness of wind when speech is also present. Limitations of this study include use of a limited number of hearing aids, normal hearing participants, one wind speed, and hearing aids programmed for one degree of hearing loss and configuration.

Appendix A

<u>Manufacturer A</u>

Venting: occluded

Omnidirectionality

Acoustic Scene Analyzer: Quiet: default expansion, machine noise: adaptation amount: up to 10 dB (setting number 2), Wind*, Speech in noise*, Noise*

Level (adaptation manger): 3

Fitting formula: e-stat

<u>Manufacturer B</u>

Venting: occluded

Omnidirectional

Programs: autopro4 (default), Quiet/Match Target, Group/Party Noise, Traffic/Intense Noise and Music: Phase canceller: disabled, antishock: moderate, NR*, WNR*, Speech Enhancement: maximum

Sensitivity control: medium (default)

Transition Control: average (default)

<u>Manufacturer C</u>

Venting: occluded

Programs: P1 multi-environment

Omnidirectional

Environment optimizer: Speech in noise (versus off)

<u>Manufacturer D</u>

Venting: occluded

Program manager: general, active (default)

Experience: long-term

Adaptation manager 3

Directionality: Surround

Noise management: Variable

My voice: on

*variable, see Table 1

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