Individual Variability in Benefit from Fixed and Adaptive Directional Microphones

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ABSTRACT

This study aimed to document improvements in speech recognition when listening through fixed or adaptive directional microphone arrays relative to listening through omnidirectional microphone arrays in a variety of near-field noise conditions. Twelve participants with mild to severe hearing loss were recruited. Data were analyzed in a manner to facilitate discussion of both group and individual performance. The activation of directional microphones significantly improved speech recognition in all listening conditions when compared to omnidirectional listening conditions. Significant differences in speech recognition performance were not observed between fixed and adaptive directional microphone conditions. Analysis of individual outcomes shows a wide range of both absolute speech recognition scores and directional benefit across treatment conditions.

KEYWORDS: Hearing aids, audiology, directional microphones, adaptive directional microphones, directional benefit

Learning Outcomes: As a result of this activity, the participant will describe the magnitude of directional benefit experienced by hearing aid wearers and define the approximate differences between fixed and adaptive directional microphone systems.

Among behind-the-ear (BTE) hearing aids, the directional microphone array has nearly become a ubiquitous feature. Clinical efficacy of directional microphone systems has been illustrated as the only means for consistently improving speech recognition in background noise (see Ricketts1 and Bentler2 for review). For the purpose of this discussion, directional microphone systems will be assumed to function in a manner that maintains a prescribed sensitivity to a signal in front of the listener (on axis) while reducing the system’s sensitivity to signals arriving from all other directions (off axis). Throughout this discussion, the behavior...
of directional microphone systems will be characterized in several manners: fixed directionality will refer to a system that retains a static, unchanging directional polar response; automatic directionality will refer to a system in which the microphone mode is automatically changed from omnidirectional to directional; adaptive directionality will refer to the behavior of a directional microphone system to adapt the polar response in a manner that yields the greatest reduction of off-axis signal power. Finally, a directional microphone system that automatically switches between omnidirectional and directional processing and demonstrates adaptation within the directional mode will be referred to as automatic adaptive directionality.

Directional benefit will be defined as the difference in performance between omnidirectional and any of the discussed directional microphone modes.

Several studies have investigated relative benefits provided by fixed directional systems and adaptive directional systems. The results of these studies have been mixed. Ricketts and Henry demonstrated a significant advantage for adaptive directional processing in the presence of a single, near-field, moving noise source that roved among multiple loudspeakers around the listener. A significant advantage for the adaptive directional array also was observed in test conditions that placed unmoving near-field noise sources at 90 degrees and 270 degrees relative to the listener; this observation was made with both the Hearing in Noise Test (HINT) and the Connected Speech Test. These results are similar to a second study reported by Ricketts et al. In this experiment, a single noise loudspeaker was attached to a pushcart. The loudspeaker, placed in the near-field, was moved behind the listener during the presentation of sentences in noise. An advantage was observed for the adaptive directional microphone condition with both fixed and moving noise conditions. In both of these studies, however, only mean data and main effects of microphone modes were reported.

Bentler et al published contrasting findings to the previously discussed investigations that demonstrated benefit for the adaptive directional condition. Their experimental design used the same make and model of hearing aids that were used by Ricketts and Henry; but the noise conditions differed. Specifically, testing was completed in a noise field generated by five loud speakers equally distributed between 110 and 250 degrees azimuth. Competing noise was presented from all speakers with one random speaker presented at a level 8 dB higher than the others. With the noise field configured in this manner, no significant differences were observed between fixed and adaptive directional microphone modes, suggesting that the presence of competing noise from multiple sources limited the opportunity for superior performance in the adaptive directional microphone condition relative to the fixed directional microphone condition. Their finding is unsurprising as the adaptation of a directional microphone system to suppress a noise source requires that the noise source consists predominately of direct energy that originates from a single source, as opposed to reverberant or indirect energy. This relationship was modeled by Woods and Trine, who proposed that the advantage for an adaptive directional array will be minimal as signal-to-noise ratio (SNR) falls below 9 dB and the direct-to-reverberant ratio falls below 2.5:1.

Several studies have reported on predictive factors related to directional benefit (e.g., Ricketts and Mueller; Galster et al). In each of these studies, the correlation between select traits of the individual participants and the benefit from directional microphones is evaluated. The nature of these studies, to report individual data for the purpose of correlational analysis, also allows insight into the range of performance within the data set. Ricketts and Mueller reported on fixed directional benefit across three earlier studies. Within the sample, individual directional benefit ranged from as little as 0.3 dB to as much as 7.6 dB, the HINT was used in all testing. In an analysis of 70 participants, Galster et al observed a greater range of fixed directional benefit using the HINT. This study also contrasted open-canal and occluding hearing aid fitting configurations. The range of directional benefit observed in open-canal hearing aid fittings fell between –2 dB and 5 dB. The range of benefit observed in occluding hearing aid fittings fell between –3 dB and 10 dB. This range for the occluded condition is skewed by the performance of a

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single participant, whose benefit score was $-3$ dB. This outlying data point would be otherwise obscured in the reporting of mean data alone, as the next closest measure of individual benefit was 0 dB.

The studies that have reported behavioral differences between fixed and adaptive directional arrays follow common trends in data reporting. Specifically, data are shown as mean performance across treatment conditions and variability within the sample is shown as one standard deviation around the mean, indicating that 68.2% of the data fell within this range. Of course, this assumes that the data are normally distributed or they have been transformed in a manner that results in a normal distribution. Although one can learn to understand the variability reported by standard deviation or standard error, these metrics lack the insight added by the reporting of individual data. For instance, reporting of individual data allows for clear interpretation of outlying data points or those that fall near the minimum or maximum measurement. Yet, reporting of individual data are often cumbersome; a dense cluster of data points may challenge the visual segregation across treatment conditions. One option that satisfies the tendency to report mean data while illustrating additional information within the data set is reporting data with box plots illustrating the distribution of data at five intervals: sample minimum, lower quartile, median, upper quartile, and sample maximum. Common variations on this method of reporting include displaying outliers rather than sample minimum and maximum, inclusion of the sample mean, or reporting data at the 5th and 95th percentiles. This nonparametric method of data reporting is not derived from an assumption of the underlying statistical distribution, as are the standard deviation and standard error. An additional benefit from representing data in this manner is the opportunity to visualize skewness in the data set. This is not to suggest that box plots are a preferred means of reporting data in all cases, rather this discussion is intended to elucidate that some common methods of reporting data obscure trends and valuable observations within the data set.

This article reports on a subanalysis of data from a larger study. The experimental goals of this study focused on better understanding of the benefits among different implementations of similar directional microphone technologies. The analysis of these results will focus on leveraging methods of data analysis that are descriptive of the data set and trends within that data set and individual performance.

**METHODS**

**Participants**

Twelve adults (seven male, five female) with symmetric mild to severe sloping high-frequency hearing loss were recruited for participation in this study. Audiometric details for the participant sample are shown in Fig. 1. The participants’ ages ranged between 50 and 79 years with a mean of 67 years. All participants had experience with hearing aid use and participation in research studies. Informed consent documentation was reviewed; this included a description of study methodology, the required involvement, and any risks or benefits associated with participation. Copies of signed consent documents were provided to participants after consultation. All participants were provided a stipend for their participation and were compensated for travel expenses to and from the research facility.

**Hearing Aid Selection and Fitting**

Four different bilateral pairs of commercially available BTE hearing aids were selected for use...
in this study. The selected hearing aids, manufactured by four different companies, are a representative sample of premium technology BTE hearing aids available in 2012. Hearing aid selection was based on the availability of discrete control of directional microphone modes in programming software. Specifically, each of the hearing aids included in this analysis allowed for manual assignment of omnidirectional, fixed directional, and adaptive directional modes. All BTE hearing aid fittings utilized full-shell occluding earmolds coupled to the hearing aids with standard diameter tubing.

Probe microphone measures were completed with an Audioscan Verifit (Etymotic, Design, Inc.; Dorchester, ON, Canada). Verification of the real-ear-aided response was performed using the International Speech Test Stimulus (Holube et al11) presented at 55-, 65-, and 75-dB sound pressure level (SPL). This verification was performed to ensure that the output of each hearing aid between 500 Hz and 4,000 Hz matched NAL-NL1 prescriptive targets within 5 dB. The in situ hearing aid response for all directional modes was manually matched to the omnidirectional response to avoid any differences in audibility among microphone conditions. All other accessible signal processing features, with the exception of feedback suppression, were deactivated for the duration of the study. This included the deactivation of wireless functionality.

Test Materials and Conditions
Participants were tested at one of three SNRs (5, 0, or −5 dB). Test SNR selection was made based on performance observed during two practice trials of the test material described below. The selected SNR was the one with which the participant performed most closely to 50% correct. During testing, speech was presented in the sound field from the speaker located at 0 degrees azimuth at 75-, 70-, or 65-dB SPL, competing noise was always presented at 70-dB SPL. A 30-second period of steady-state speech-shaped noise was presented at 70-dB SPL prior to the onset of each trial to ensure all automatic or adaptive hearing aid behavior was activated. The competing noise played without interruption throughout each condition. Test conditions included two speaker configurations: a “diffuse” noise condition, with noise presented from seven symmetrically distributed off-axis speakers and a second test condition, termed “discrete,” presented noise from a single speaker at one of three angles. The discrete speaker locations were presented in the following order: 180, 90, and 135 degrees. Three microphone conditions were tested in each noise configuration: omnidirectional, fixed directional, and adaptive directional for each of the four hearing aids. Order of conditions was randomized and counterbalanced across participants.

The Computer-Assisted Speech Perception Assessment (CASP) was selected as test material.12 The CASP is a test of speech recognition in noise that is administered using a fixed SNR. The selected test corpus features a recorded female talker who uses a carrier phrase, “Please say the word . . . ,” followed by a consonant-vowel-consonant (CVC) word. A simultaneous speech-shaped steady-state noise was presented for all test conditions. Each list of words contained 10 CVC words. Each condition included two lists of 20 randomized words. Participants repeated back any words or phonemes that they heard after the carrier phrase. There was no restriction to response time and no performance feedback was provided.

Test presentation, randomization, and scoring were managed through the CASPA program, version 3.3a and Adobe Audition (Adobe Systems, Inc.; San Jose, CA). All stimulus presentation was done through eight Genelec 8030A loudspeakers (Genelec, Rii-salmi, Finland) spaced 45 degrees apart. Each speaker was placed 1 m from the listener, who was seated in the center of the speaker array. Power was supplied by an APC H15 Power Conditioner (APC by Schneider Electric; West Kingston, RI). Audio routing from a personal computer was managed by an M-Audio Fast Track Pro (inMusic Brand; Cumberland, RI) and AMX Auto Patch Precis DSP sound card (AMX; Richardson, TX). All levels were calibrated to A-weighted targets using a Larson Davis 824 sound level meter (Larson Davis, APCB Piezotronics Div., Depew, NY).

The automatic and adaptive behavior of each hearing aid was verified by playing a fixed,
on-axis speech signal while systematically increasing levels from all seven noise speakers and monitoring the electroacoustic output of each hearing aid using a Knowles Electronics Manikin for Acoustic Research (KEMAR) mannequin (KEMAR; G.R.A.S. Sound and Vibration A/S, Skovlytoften, Denmark) that was fitted with the hearing aids under investigation. Objective judgments of the hearing aid switching behavior were made by monitoring ear-simulator levels and cross-checked against subjective listening reports. The change from omnidirectional to directional microphone modes was observed as a decrease in the root mean square (RMS) output of all tested hearing aids; subjective observations were in clear agreement with these measurements. The adaptation of each directional microphone system was verified in a similar manner. A single noise source at 180 degrees was presented behind the KEMAR until a switch from omnidirectional to directional was observed. The noise source was then changed to the speaker located at 90 degrees. As with the change from omnidirectional, the behavior of each adaptive directional microphone array to converge on the noise source located at 90 degrees was objectively observed in the recorded RMS levels and supported by subjective judgments of the researcher. The noise level of 70-dB SPL was found to be the lowest noise level at which all of the hearing aids under test automatically transitioned from omnidirectional to fixed or adaptive directional modes.

RESULTS
The following analyses have been selected to illustrate both group and individual performance in the data set. Prior to statistical analysis, individual percent correct were converted to rationalized arcsine transform units (RAU) to account for error in the variance. Following the arcsine transform, the Shapiro-Wilk test of normality revealed that the data were not normally distributed. As a result of this observation, a Wilcoxon signed ranks test was used to evaluate differences among treatment conditions. This test is a nonparametric alternative to the t test and appropriate for smaller sample sizes such as this one. Significant differences were observed between treatment conditions: in both the diffuse and discrete noise conditions, the fixed directional microphone condition showed significantly improved performance when compared with the omnidirectional conditions (p < 0.001) and the adaptive directional microphone condition showed significantly improved performance when compared with the omnidirectional conditions (p < 0.001), indicating that both fixed and adaptive directional microphone arrays provide significant benefit when compared with an omnidirectional microphone mode in both diffuse and discrete noise. All other comparisons were nonsignificant, suggesting that the adaptive directional microphone mode did not significantly improve performance over the fixed directional microphone mode in either the diffuse or discrete noise conditions. For reference, Table 1 provides data for one standard deviation and standard error of the mean for each of six test conditions, combining microphone modes and speaker configurations.

Fig. 2 shows the results of testing in the diffuse noise condition. Word recognition (shown as RAU) is plotted as a function of all three microphone conditions. Overall performance improved in both the fixed and adaptive directional conditions relative to the omnidirectional condition. Mean directional benefit provided by the fixed directional microphone

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13 SEMINARS IN HEARING/VOLUME 34, NUMBER 1 2013

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was 12 RAU whereas mean adaptive directional benefit was 15 RAU.

Fig. 3 shows the results of testing in the discrete noise condition. Word recognition (plotted in RAU) is plotted as a function of all three microphone conditions. Mean directional benefit provided by the fixed directional microphone was 19 RAU whereas mean adaptive directional benefit was 20 RAU.

**Figure 2** For the diffuse noise test condition, percent correct word recognition transformed to rationalized arcsine transform units is shown as a function of three microphone conditions: omnidirectional, fixed directional, and adaptive directional. Box plot whiskers show the 5th and 95th percentiles, the shaded box shows the 25th and 75th percentiles. Mean performance is shown as a solid line within the box, median performance is shown as the dashed line inside the box. Abbreviations: CASPA, Computer-Assisted Speech Perception Assessment; RAU, rationalized arcsine transform units.

**Figure 3** For the discrete noise test condition, collapsed across each of three noise speaker locations, percent correct word recognition transformed to rationalized arcsine transform units is shown as a function of three microphone conditions: omnidirectional, fixed directional, and adaptive directional. Box plot whiskers show the 5th and 95th percentiles, the shaded box shows the 25th and 75th percentiles. Mean performance is shown as a solid line within the box, median performance is shown as the dashed line inside the box. Abbreviations: CASPA, Computer-Assisted Speech Perception Assessment; RAU, rationalized arcsine transform units.

**Figure 4** Percent correct speech recognition is shown for each individual participant and each of three microphone modes: omnidirectional, fixed directional, and adaptive directional. Each panel shows performance in a different noise configuration: (A) diffuse noise; (B) discrete noise from 90 degrees; (C) discrete noise from 135 degrees; (D) discrete noise from 180 degrees.
Fig. 4 shows individual percent correct performance for each participant across each of the three tested microphone modes. Each of the four panels shows data from one of the four noise conditions. Fig. 4A shows diffuse noise, Fig. 4B shows discrete noise at 90 degrees, Fig. 4C shows discrete noise at 135 degrees, and Fig. 4D shows discrete noise at 180 degrees. It is clear, across all four panels, that the majority of participants demonstrate consistent directional benefit across all test conditions. Several participants were selected for discussion. These participants represent a range of performance within the data set including high and low performers and an individual who performed closely to the group mean.

Participant 7 performed at levels equivalent or superior to all other participants, in all microphone and noise conditions. However, the directional benefit (i.e., the difference between directional and omnidirectional performance) experienced by participant 7 was of similar magnitude to the other participants. In contrast, participant 9 performed more poorly than the group mean within any single condition, but shows directional benefit that is similar in magnitude to the rest of the participants. The mean data suggest that participants’ absolute performance in the fixed and adaptive directional conditions was similar. In several cases, however, individual performance deviates from this observation. In Fig. 4A, for instance, 4 of 12 participants performed more poorly with the fixed directional microphones when compared with adaptive directional microphones. In Fig. 4B, one participant revealed a noteworthy difference between directional conditions with a 6% advantage for the fixed directional condition compared with the adaptive directional condition. In Fig. 4C, 2 of 12 participants showed more than a 5% advantage for the adaptive microphone condition. In Fig. 4D, one participant showed an advantage for the fixed directional condition whereas the rest of the participants showed similar performance between the two directional conditions.

**DISCUSSION**

In agreement with the observations of Bentler et al., the diffuse noise field used in this study did not reveal performance differences between the fixed and adaptive microphone arrays. Significant improvements in speech recognition for both directional microphone conditions when compared with the omnidirectional performance were observed in these diffuse noise conditions. Also expected in this diffuse noise condition was the observed parity between fixed and adaptive directional microphone modes.

The discrete noise test conditions were expected to generate sufficiently direct off-axis noise to trigger adaptation of the directional microphone arrays. Electroacoustic verification suggested that all of the hearing aids under test demonstrated repeatable automatic and adaptive behavior in this sound field. As a result of this observation and previous reports of adaptive directional advantage in similar noise configurations (e.g., Ricketts et al.), it was expected that the adaptive directional microphone test conditions would yield some advantage when compared with performance in the fixed directional test condition. As shown in Fig. 3, this was not observed. Performance in both the fixed and adaptive directional microphone conditions was similar in mean, range, and distribution of performance.

It has not been common practice to publish descriptive reports of human subject directional microphone performance that share more than mean data within treatment conditions and a metric that characterizes variability around that mean. Although several publications have discussed individuals’ data with a focus on directional benefit, these publications have not discussed absolute performance of the individual within treatment conditions. Fig. 4 shows individual performance for omnidirectional, fixed directional, and adaptive directional microphone conditions across each of the four noise conditions. These figures illustrate the significant directional benefit that was observed in the diffuse noise condition and across the discrete noise conditions. The overlapping gray lines also illustrate the lack of consistent difference between fixed and adaptive directional microphone conditions. For that reason, the following discussion of directional benefit will report mean benefit observed within each of the three microphone conditions and across the four noise conditions. Several noteworthy individual differences appear in the
data. There is a consistent trend for the absolute performance of participant 9 to be lower than his counterparts. Participant 9’s mean directional benefit of 21% was of similar magnitude to the group mean directional benefit of 18%. Participant 7 stands out as demonstrating consistently high absolute performance with a tendency to outperform the majority of participants in omnidirectional and both directional conditions. Yet for this individual, the magnitude of mean directional benefit is similar to that experienced by participant 9. These two examples characterize the range of absolute performance data. In a third example, participant 1 averaged directional benefit of 6% as compared with the group average of 18%. The participant’s benefit was not a function of any extremes in absolute performance, rather participant 1 performed slightly above average in the omnidirectional microphone conditions and slightly below average in the directional microphone conditions, reducing the observed directional benefit.

CONCLUSION
Although the rationale for individual differences and similarities is beyond the scope of this investigation, these observations provide valuable clinical information. Trends within the individual data clearly show that interpretation from the group averages would not adequately prepare a clinician to understand the variability an individual patient may experience in different listening situations. In the examples discussed here, the clinician can begin by interpreting average data to establish broad expectations related to the efficacy of both fixed and adaptive directional microphone arrays. Unilateral interpretation of these data, however, would not prepare that same clinician for the variability among individuals that occurs on a case-by-case basis. Understanding performance of individuals, particularly those outlying the average, provides useful insights that support the development of counseling strategies that can better prepare patients for realistic expectations in their aided outcomes.

REFERENCES