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Factors influencing individual variation in perceptual directional microphone benefit

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Abstract

Background: Large variations in perceptual directional microphone benefit, which far exceed the variation expected from physical performance measures of directional microphones, have been reported in the literature. The cause for the individual variation has not been systematically investigated.

Purpose: To determine the factors that are responsible for the individual variation in reported perceptual directional benefit.

Research Design: A correlational study. Physical performance measures of the directional microphones obtained after they had been fitted to individuals, cognitive abilities of individuals, and measurement errors were related to perceptual directional benefit scores.

Study Sample: Fifty-nine hearing-impaired adults with varied degree of hearing loss participated in the study.

Data Collection and Analysis: All participants were bilaterally fitted with a Motion behind-the-ear device (500 M, 501 SX, or 501 P) from Siemens according to the NAL-NL2 prescription. Using the BKB sentences, the perceptual directional benefit was obtained as the difference in speech reception threshold measured in babble-noise (SRTn) with the devices in directional (fixed hyper-cardioid) and in omnidirectional mode. The SRTn measurements were repeated three times with each microphone mode. Physical performance measures of the directional microphone included: the angle of the microphone ports to loudspeaker axis, the frequency range dominated by amplified sound, the in situ signal-to-noise ratio (SNR), and the in situ three-dimensional, articulation-index weighted directivity index (3D AI-DI).

The cognitive tests included: auditory selective attention, speed of processing, and working memory. Intra-participant variation on the repeated SRTns and the inter-participant variation on the average SRTn were used to determine the effect of measurement error. A multiple regression analysis was used to determine the effect of other factors.

Results: Measurement errors explained 52% of the variation in perceptual directional microphone benefit (95% CI: 34% to 78%), while another 37% of variation was explained primarily by the physical performance of the directional microphones after they were fitted to individuals. The most contributing factor was the in situ 3D AI-DI measured across the low frequencies.

Conclusions: Repeated SRTn measurements are needed to obtain a reliable indication of the perceptual directional benefit in an individual. Further, to obtain optimum benefit from directional microphones the effectiveness of the microphones should be maximized across the low frequencies.

Key words:

hearing aid, directional microphone, directivity index, directional benefit, test-retest measurements, speech reception threshold in noise, in situ measurements

Abbreviations:

3D = three-dimensional; AI = articulation index; ASA = auditory working memory; BB = broad band; B&K = Brüel and Kjær; BKB = Bamford-Kowal-Bench; BTE = behind-the-ear; CI = confidence interval; DI = directivity index; f_{amp} = frequency range dominated by amplified sound; HF = high-frequency; HINT = hearing in noise test; ILTASS = international long-term average speech spectrum; ISTS = international speech test signal; LF = low-frequency; KEMAR = Knowles’ electronic mannequin for acoustic research; NAL-NL2 = National Acoustic Laboratories’ non-linear prescription, version two; PTA = pure tone average; REIG = real-ear insertion gain; SD = standard deviation; SE = standard error; SNR = signal-to-noise ratio; SoP = Speed of Processing; SRTn = speech reception threshold in noise; TEA = test of everyday attention; WM = working memory

Introduction

Difficulty communicating in noisy environments drives many people to seek professional help with their hearing problem. It is well-established that hearing-impaired people require a better signal-to-noise ratio (SNR) than those with normal hearing for understanding speech in background noise (e.g. Plomp, 1978). Improving the SNR is therefore an important goal of hearing aid signal processing schemes. Currently, the hearing instrument feature that most effectively improves the SNR is the directional microphone, provided speech and noise arrive from different directions, at least one of the signals is within the critical distance, and the noise either arrives equally from all directions or predominantly from rearward. The improvement in SNR is achieved through the directional microphone's sensitivity pattern. Depending on its configuration, a directional microphone is more sensitive to sounds arriving from a particular direction (e.g. the front) than to sounds arriving from other directions. For excellent reviews of directional microphones, including detailed descriptions of how they work and their effectiveness in different acoustic environments, see Ricketts (2001), Chung (2004), and Dillon (2012).

The physical performance of a directional microphone is often expressed by its directivity index (DI), which reports the ratio of sensitivity to on-axis sounds relative to sensitivity averaged across all other directions. When the target speech is close and frontal, and the noise arrives equally from all directions, an increase in DI by 1 dB roughly translates into a 1 dB SNR improvement. The DI varies with frequency. Because some frequencies contribute more to speech understanding than others, the importance function used in the articulation index (AI) model can be used to weight the DI. Referred to as the AI-DI (Killion et al., 1998), this measurement is a better indicator of the directional microphone's effect on speech understanding across the frequency range. For conventional first-order directional microphones, the DI measured with the hearing aids on a mannequin typically varies between 2.5 and 3.5 dB, depending on microphone placement and sensitivity pattern (e.g. Dittberner and Bentler, 2003). The AI-DI values may be slightly higher (e.g. Compton-Conley et al., 2004), especially when the DI extends to the high-frequency region (e.g. Valente, 2000).

The perceptual benefit of directional microphones is commonly evaluated by comparing speech-in-noise performance with directional and omnidirectional microphones. One of the most common test paradigms involves adaptively changing the level of speech, presented in constant-level background noise, to determine the SNR at which 50% of speech is recognised. The result of such a measurement is referred to as the speech reception threshold in noise (SRTn) and is expressed in dB SNR. Depending on the speech and noise material, an improvement in SNR (or SRTn) of 1 dB can, on average, result in 10-20% improvement in speech understanding (e.g. Young et al., 1982; Festen and Plomp, 1990; Kollmeier and Wesselkamp, 1997), which is a substantial gain.

Freyaldenhoven et al. (2005) summarized the perceptual directional benefit reported in seven studies, including their own, and commented on the large range of benefit scores. Substantial individual variation in perceptual directional benefit has also been commented on in Walden et al. (2005). The seven studies reviewed in Freyaldenhoven et al. (2005) all measured the perceptual directional benefit as the difference in SRTn obtained with a directional and an omnidirectional microphone, but there were significant procedural differences between studies. Table I shows a similar summary of nine studies that have each reported the perceptual directional benefit obtained from SRTn measurements using sentences presented in a diffuse noise field. Each of these studies reported an average directional benefit that corresponds well with reported AI-DI values for directional microphones of the time. The lowest average benefit was 2.6 dB and the highest 4.5 dB.

In theory, a given directional instrument should provide the same SNR benefit to any user. It is therefore curious that large ranges in perceptual benefit around the mean have been reported, with the range varying from 6 to 14 dB. The ranges suggest that some individuals obtained an SNR advantage from the directional microphone of 10-11 dB, while others obtained none, or even performed slightly worse with the directional microphone (cf. Table I). The variation in perceptual directional benefit appears to be independent of such factors as age (Wu, 2010; O'Brien et al., unpublished data), degree of hearing loss (Jespersen and Olsen, 2003; O'Brien et al., unpublished data), configuration of hearing loss (Ricketts & Mueller, 2000), and vent size/leakage (Ricketts, 2000; O'Brien et al., unpublished data). Some variations could be expected from individual head, torso, and pinna shadowing effects; individual on-axis position of the microphone ports; and random SRTn measurement errors (Ricketts et al., 2001; Bell et al., 2010). Desloge et al. (2010) looked at the impact of hearing aid wearers' physical characteristics on first-order hearing aid directionality and found that torso size, ear-canal-to-shoulder distance, and pinna flare, among others, were not major contributors to individual variability in directional benefit. Nevertheless, variation in physical SNR variations, especially those measured in situ on test participants, and measurement errors have not been systematically investigated, and could be greater than anticipated.

More recently, studies have emerged suggesting that individual variability in hearing aid benefit may be explained to some degree by cognitive abilities. For example, several studies have found that cognition – particularly working memory – affects performance with different, or unfamiliar, time constants (Gatehouse et al., 2003; Lunner et al., 2007; Rudner et al., 2008; Cox and Xu, 2010). Working memory skills have also been demonstrated to affect the spatial separation ability in bilaterally fitted hearing aid users (Neher et al., 2009), while Dawes et al. (2010) found that differences in hearing aid benefit could be partly explained by performance on more complex cognitive tasks that challenged speed of processing and selective attention and switching. Further, both behavioral data (Humes, 2007) and measurements of the neuroanatomical structure of cognitive brain regions (Wong et al., 2010), have demonstrated that when controlling for audibility, cognitive factors play a role in explaining individual variation in speech perception abilities in noise. Cognitive decline is also associated with aging. However, age-related changes in brain structure and function are not uniform across the whole brain or across individuals, and hence cognition varies greatly in older individuals (e.g. Glisky, 2007). Taken together, the variation in directional benefit could be due to cognitive processes that may affect a person's ability to utilize the SNR improvement.

The perceptual directional benefit scores referred to in Table I were obtained in controlled laboratory settings. Other studies have reported that performances measured in the laboratory with directional microphones are not good predictors of real-life performances (Walden et al., 2000; Cord et al., 2002; Cord et al., 2004). Factors other than those explaining the variation in directional benefit measured in the laboratory may contribute to this finding. However, it is possible that if we better understood the factors that cause the variation in directional benefit measured in a controlled environment, it may lead to a better understanding of, or at least a hypothesis for, the variation in real-life performance with directional microphones.

Given this background, the broad objective of this study was to determine the factors that decrease or increase the benefit obtained from directional microphones in individuals and their proportional contribution to the inter-participant variability. Specifically, the study was designed to investigate whether the variation in directional benefit measured from person to person is predominantly due to a variation in physical SNR improvement after the directional instrument has been fitted to the individual, to variation in the ability to use an SNR improvement, to measurement error in either the physical or perceptual measures, or to a combination of these. The factors that may cause the individual variation in physical SNR benefit include room acoustics, distance, directional pattern, and vent and amplification paths. Factors that may cause the individual variation in people's ability to use the SNR improvement include cognitive function.

Methodology

Participants

A total of 63 hearing-impaired listeners were recruited for this study. This number ensured sufficient statistical power for multiple regression testing with up to 6 independent variables. The first three recruits were pilot participants and, as changes were made to the implementation of several tests after their participation, data from these three people have been discarded together with data from one participant whose SRTns were atypically high. The remaining 59 participants included 22 females and 37 males with an average age of 74 years (SD = 7.1 years). The standard deviation of age was reduced to 5.8 years when ignoring the two youngest and the oldest participants of 54 and 91 years, respectively. All participants had a sensorineural hearing loss with the average bilateral pure tone average (PTA), measured across 0.5, 1.0, and 2.0 kHz, being 41 dB HL, varying from 25 to 58 dB HL. Figure 1 shows for each audiometric frequency the mean threshold level for left and right ears together with the standard deviation, and the minimum and maximum values. For all but three participants, the difference in PTA between left and right ear was less than 10 dB. The remaining participants displayed differences of 10, 12, and 13 dB. Of the 59 participants, 51 had experience with amplification, while eight had none.

Hearing devices and fitting

The Motion 500 M, 501 SX, and 501 P behind-the-ear (BTE), dual-microphone devices from Siemens were used in this experiment to cover a wide range of hearing loss. All devices were digital, with multi-memory, fast-acting wide dynamic range compression. The devices were equipped with a range of adaptive gain features such as noise reduction and adaptive directionality, although such features were deactivated for this study. Omnidirectional and fixed hypercardioid directional microphone modes were implemented using either the Omnidirectional or Directional Test Settings option in Connexx. Among the three devices, the Motion 500 M distinguished itself by using a different chipset, and by having the microphone ports further apart and placed on the side of the hearing instrument. According to the directional polar patterns obtained in the free field at two frequencies (0.5 and 2.0 kHz) for one sample of each model, the Motion 500 M in particular provided more directionality at 0.5 kHz, see Figure 2.

Each participant was bilaterally fitted with a hearing aid model appropriate for the degree of hearing loss using custom earmolds with individually drilled vents. Coincidentally, the three different hearing aid models were equally represented across participants. Two programs were created with gain set to match the NAL-NL2 target (Keidser et al., 2011), and with the microphone in omni mode in program one (P1) and in directional mode in program two (P2). The Test Settings function in Connexx was used to ensure that all adaptive features were disabled and that the correct microphone mode was selected. Using the Aurical FreeFit system, the gain-frequency response was verified in both programs with real-ear insertion gain (REIG) measurements using the International Speech Test Signal (ISTS; Holube et al., 2010) at 65, 55, and 80 dB SPL. During the verification measurements, participants were positioned 1 metre from the loudspeaker (Tannoy 800) at 0° azimuth.

Protocol

Each participant attended two appointments. During the first appointment, the purpose of the study and the tasks were explained, and a consent form was signed. Otoscopy was performed, followed by threshold measurements and impression taking for new molds. Vent sizes were chosen according to the participants' degree of hearing loss and past experience. The median vent size was 1.81 mm and varied from 0 to 3.4 mm. The participants then completed a series of cognitive tests. A subset of the Test of Everyday Attention (TEA; Robertson et al., 1996) was administered to obtain information about auditory selective attention, and speed of processing. Working memory was measured with the Reading Span Test (Daneman and Carpenter, 1980). These tests and their scoring methods are outlined in further detail below.

During the second appointment, participants were first fitted with a pair of devices as described previously. Prior to fitting, the exact vent diameter was measured with a pin gauge at the outside end of the earmold bore. From the four REIG measurements obtained for the 65 dB SPL input signal (two ears by two microphone modes), the lowest frequency at which the REIG curve exceeded 3 dB was noted. This frequency indicated the start of the frequency range dominated by amplified sound (f_{amp}), and hence the frequency range over which the directional microphone would be effective; i.e. a lower f_{amp} would indicate more effect. After hearing aid fitting, the angle of the microphone ports to the loudspeaker axis was measured for each ear using a protractor that had a small spirit level attached horizontally along the base, and a movable plastic arm attached to the base's center. The protractor was first positioned alongside the participant's ear such that the bubble in the spirit level was centered. The plastic arm, which had a black line drawn along it, was then moved until its line passed through both microphone ports, and the angle formed by the two ports was recorded. The participants then completed speech-in-noise testing, measurement of the in situ SNR, and measurement of the in situ three dimensional (3D) AI-DI, which are each described in further detail below. During these measurements, the experimenter used a Tek remote control to switch between the omnidirectional and directional programs as required. Successful switching was verified by asking the participant to confirm that one or two beeps were heard. At the conclusion of the appointment, the participants were paid a small gratuity to cover transport costs.

Cognitive tests

To measure auditory selective attention (ASA), the participants were presented with a series of low-frequency (LF) tones in a slightly irregular tempo mixed with randomly placed high-frequency (HF) tones[1]. The tones were played back through a chain of equipment that included a Yamaha Natural Sound CDX-530 CD player, an Interacoustics AC40 clinical audiometer, and an Aaron loudspeaker. The participants were asked to imagine they were in an elevator in which the visual floor indicator was broken and LF tones were used to indicate the passing of floors. The participants' task was to count the LF tones, ignoring the HF tones, to indicate at which floor the elevator eventually stopped. During testing, participants, aided with their own hearing aids, faced the loudspeaker from a distance of approximately 1 metre.

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[1] A clean version of this test was created and used as the original recordings contained a weak, but audible, echo of each tone.

Stimuli were initially presented at 65 dB SPL. The verbal instructions on the stimulus CD were used to determine if the level needed to be adjusted to make the tones “comfortable and easy to hear”. No one required the level adjusted. The raw score was the number of correct items out of 10. With reference to normative data, this score was subsequently scaled based on the participant’s age.

The speed of processing (SoP) was extracted from a test in which the participants were shown a series of visually presented elevators moving up and down as indicated by the direction of large arrows displayed every so often. The task of the participants was to follow the elevators and count up and down as required. The participants were asked to count out loud and to say ‘up’ and continue to count upwards when encountering an upward arrow and to say ‘down’ and start counting backwards when seeing a downward arrow. Each of ten trials was timed. The timing score was the total time taken to complete the trials that produced a correct answer, divided by the number of switches (between up and down) in the correct trials. As above, with reference to normative data, the timing score was subsequently scaled based on the participant’s age, with a higher score assigned to a faster time.

A slightly revised version of the reading span test was used to measure working memory (WM). The revisions consisted of changing a few words to more commonly used words in Australia, such as birch, larch, sauna, and pupil that were changed to tree, bush, shower, and student, respectively. Sentences were presented one by one on a computer screen for 2500 msec with an inter-sentence interval of 3000 msec. After each sentence, participants were asked to indicate if the sentence was meaningful or not. After each block of 3 sentences, increasing over time to blocks with up to 6 sentences, the participants were asked to recall either the first or the last word of each sentence. The score was the total number of correctly recalled words.

Speech-in-noise testing

SRTn measurements were obtained using an adaptive procedure in which the level of speech was gradually changed while the level of noise remained constant. Speech and noise were the Australian Bamford-Kowal-Bench (BKB-A) sentences (Bench et al., 1979) and an eight-talker babble noise from the NAL CD of Speech and Noise for Hearing Aid Evaluation (Keidser et al., 2002). The BKB sentences were produced in England and are typically used with British English speaking populations. They form the baseline for the hearing in noise test (HINT) sentences (Nilsson et al., 1994) widely used with the American English speaking populations. Both stimuli were filtered to match the International Long-Term Average Speech Spectrum (ILTASS; Byrne et al.,1994) and were presented from a computer through an RME Hammerfall DSP Multiface II audio interface and two four-channel amplifiers (Yamaha XM4080) to five dual-concentric loudspeakers (Tannoy 800). Speech was presented from a loudspeaker situated one metre in front of the participants. Babble noise was presented uncorrelated from four loudspeakers situated at $\pm 45^0$ and at $\pm 135^0$ azimuth at a distance of two metres from the participants. The presentation level of the continuous background babble noise was kept constant at 55 dB SPL, while the level of speech was changed adaptively, starting at 10 dB SNR. The adaptive procedure was controlled by a software program that cycles through three phases during which the step size is gradually reduced from 5 to 2 to 1 dB over a minimum of 16 sentences, aiming for a standard error (SE) of measurements of no more than 0.8 dB, or a presentation of maximum 32 sentences (Keidser et al., submitted). A morphemic scoring method was used in which every meaningful unit of each word was scored. For example, “postman” and “boys” each consist of two morphemes (‘post’ + ‘man’ and ‘boy’ + ‘s’) and were thus given a score of 2 if repeated correctly. Three SRTn measurements were obtained with each of the two microphone modes in a balanced, randomized order across participants, including measurements of the SNR needed to obtain 25% and 75% correct with each microphone mode. These measurements are not reported in this paper. Testing took place in a room fitted out with carpet, ceiling absorption panels, and curtained sections to produce a listening environment with an acoustic characteristic closer to typical living rooms (T_{60} ~ 0.4 msec).

In situ signal-to-noise ratio measurements

To obtain the in situ SNR measurements, the same room, stimuli, and loudspeaker arrangement as for the SRTn measurements were used. In addition, a probe microphone was inserted in each of the participants’ ears. The probe microphones were connected to the RME Hammerfall DSP Multiface II audio interface via a dual channel pre-amplifier (built in-house). A program developed in-house handled the presentation of speech and babble noise in the free field, recorded the hearing aid processed output at the ear canal, and estimated the in situ SNR for each ear. The speech sequence included 16 BKB sentences that were presented successively in babble-noise with each sentence (and corresponding noise sequence) presented twice in succession, first in a normal condition and then with the speech phase reversed. The input SNR was individually selected for each participant and constituted the average of the SRTn measurements obtained across microphone modes and repetition for that participant. During playback, participants were instructed to look straight ahead, fixing their gaze at the loudspeaker in front of them. From the recorded output file, two separate files were created, with one containing only the recorded frames with speech presented normally and the other containing the recorded frames containing the phase-reversed speech. Using the method proposed by Hagerman and Olofsson (2002), the levels of the hearing aid processed speech and noise in situ were estimated by adding and subtracting the two output files, respectively, and from these levels the in situ SNR was derived. The in situ SNR was computed at each one-third octave frequency from 75 to 24190 Hz, from which SNRs for the broad band (BB), and for low (< 2000 Hz) and high (≥ 2000 Hz) frequencies were extracted. Because the analysis was based on short frames that shifted frequently between the two stimulus conditions, it is assumed that undesired effects from slight head movements were sufficiently reduced. The in situ SNR was obtained once for each microphone mode.

To investigate to what extent the room acoustics affected differences between the three hearing aid models, in situ SNR measurements were obtained with a set of each model fitted to a Knowles Electronics Mannequin for Acoustic Research (KEMAR) equipped with Zwislocki couplers and inactive microphones to simulate an average ear canal cavity. For these measurements, closed molds were used, the devices were programmed for a 50 dB HL flat hearing loss, and the input SNR was 0 dB. The effect of microphone angle was also investigated by gradually changing the length of the tube connecting the device with the mold to obtain in situ SNR measurements for microphone angles of 0, 15, 30, and 45 degrees. The results obtained across low and high frequencies are shown in Figure 3. Two observations were made: the Motion 500 M improved the SNR at low frequencies more than the other two devices, which would be expected from the directional polar patterns in Figure 2, and the SNR improvement at high frequencies increased with increasing microphone angle, especially for the Motion 501 devices. The latter observation is further discussed below.

The in situ 3D AI-DI

For the 3D AI-DI measurements the participants were seated in the center of a 3D array of 41 loudspeakers (Tannoy 800) installed in an anechoic chamber. Uncorrelated random noise was presented from a computer via two RME M-32 A/D digital interfaces, controlled by a HDSP-MADI card and 11 Yamaha XM4080 amplifiers through 33 of the loudspeakers. A program was developed in-house to control the playback of the noise simultaneously through the (0°, 0°) loudspeaker and through 32 loudspeakers distributed in the array by 8 loudspeakers equally spaced in the horizontal ring at each of -30^0, 0^0, and +30^0 elevation, and 4 loudspeakers at each of -60^0 and +60^0 elevation. The noise was presented for 10 sec in normal mode at a level of 63 dB SPL at the center of the array, immediately followed by 10 sec with the noise from the frontal loudspeaker phase-reversed. The power weights of Table I in ANSI S3.35 (2004) were applied to the noise presented from each loudspeaker. The hearing aid processed output was captured in situ with the probe tube microphone system described above connected to the computer via an RME M-16 A/D digital interface. The recording was used to create an output file of the noise presented in normal mode and another of the noise with the frontal stimulus phase-reversed. Using the technique described by Hagerman and Olofsson (2004), sensitivity to frontal sound was estimated from the difference between the two output files, while sensitivity to sounds from other directions was estimated from the sum of the two files. This method ensured that the adaptive gain settings were the same when recording the responses to the frontal noise and to the diffuse noise. Using equation 1 from the ANSI S3.3.5 (2004), the DI was obtained at one-third octave frequencies from 100 to 10000 Hz. Three sets of DI recordings were obtained for each microphone mode that were subsequently weighted with the AI function from ANSI S3.5 (1997). Although participants were instructed to gaze at a marked point ahead of them to keep the head in a fixed position during measurements, in a few cases (9 out of 118) one recording was greatly different to the other two and was discarded in the further analyses. From the average of stable measurements, 3D AI-DI values for the BB, and for low (< 2000 Hz) and high (≥ 2000 Hz) frequencies were extracted for each participant.

Calibration

At the beginning of the study, a calibration program produced in-house was used to obtain a set of equalization filters relating to the loudspeakers in the setup used for SRTn and in situ SNR measurements. The equalization filters were created from impulse responses measured for each loudspeaker in response to a chirp-like stimulus. Measurements of impulse responses were obtained with a ½ inch B&K 4166 microphone, situated in the undisturbed field at the position of the participants' head during testing, connected to the test computer via a B&K 2636 measuring amplifier and the RME Hammerfall DSP Multiface II audio interface. During testing, the equalization filters were applied to the stimuli to flatten their responses at the participants' listening position. A set of equalization filters was obtained and used in a similar manner in the anechoic chamber for the in situ 3D AI-DI measurements. Before each appointment, the overall output level of each loudspeaker in each test setup was verified with a sound level meter using an ILTASS-shaped random noise.

Results

Table II shows the means, standard deviations, and ranges of the results of the cognitive and physical performance tests. One participant was visually impaired and was unable to complete the WM test. Performance for this participant was predicted from average performances by other participants who obtained similar scores on the ASA and SoP tests. Significant, but weak, correlations were found between SoP and ASA ($r = 0.28$; $p = 0.03$) and between SoP and WM ($r = 0.27$; $p = 0.04$). In both cases faster processing was associated with better ASA and WM. A weak correlation between ASA and WM did not reach significance ($r = 0.22$; $p = 0.10$). Results of the only auditory test, ASA, was not significantly correlated with PTA ($r = 0.14$, $p = 0.30$), but did show, as the only cognitive parameter, a significant, but weak, correlation with age ($r = 0.32$, $p = 0.01$). This significant association disappeared, however, when ignoring the youngest and oldest participants who performed exceptionally poorly and well for their age, respectively.

For all participants, the physical performance measures were averaged across ears. In addition, benefit measures were calculated for the in situ measurements by subtracting the performance measures of the omnidirectional microphone from those of the directional microphone. The correlation between the LF and BB benefit measures were for both in situ parameters highly and significantly correlated ($r = 0.96$; $p < 0.0001$ for the SNR, $r = 0.93$; $p < 0.0001$ for the 3D AI-DI). There was also a significant correlation between the HF and BB benefit measures, but the relationship was less strong ($r = 0.37$; $p < 0.004$ for the SNR, $r = 0.70$; $p < 0.0001$ for the 3D AI-DI). Consequently, further analyses included the benefit measured in the two separate bands rather than across the entire bandwidth. Not surprisingly, the parameters f_{amp} and in situ LF benefit measures were moderately to highly and significantly correlated with each other and with the PTA and vent size ($r > |0.52|$; $p < 0.0001$). The correlations showed that participants with higher degree of hearing loss were fitted with smaller vent sizes, resulting in a larger range of frequencies dominated by amplified sound and more physical benefit from the directional microphone at low frequencies. While the in situ SNR and 3D AI-DI benefit measurements obtained at low frequencies were highly significantly correlated ($r = 0.86$; $p < 0.0001$), there was only a weak, but significant, correlation between the in situ measurements obtained at high frequencies ($r = 0.30$; $p = 0.02$), possibly due to the different acoustic characteristics of the two test rooms in which measurements were obtained.

Table III lists the average SRTns obtained with each microphone mode after each repeated measure, together with the standard deviation values. The test-retest correlations (Pearson's product-moment, r) between the three measures varied from 0.85 (test 1 vs test 3) to 0.86 (test 1 vs test 2/test 2 vs test 3) for the omnidirectional microphone, and from 0.79 (test 1 vs test 3) to 0.89 (test 2 vs test 3) for the directional microphone. These correlation coefficients are reasonably high and statistically significant ($p < 0.0001$), although, on average, about 30% of the test-retest variation is unaccounted for, presumably reflecting the degree of random measurement error in the SRTn measurements. The average directional benefit score obtained after each repeated measure and the range of benefit scores are also given in Table III and the distributions of the benefit values are further shown in Figure 4. The benefit ranges vary from 6.3 dB to 9.2 dB across the three sets of SRTn measurements, which is in good agreement with results presented in Table I. Table III also shows the results when averaging the SRTn measurements across repetition for each microphone mode before calculating the perceptual directional benefit. It is notable that when reducing the effect from random measurement errors, the benefit range is reduced to 5.0 dB, and no participants showed a negative benefit. From the three sets of directional benefit values a mean intra-participant variance (SD_s^2) of 2.1 dB^2 is obtained, which suggests an expected measurement error variance of $SD_s^2/3 = 0.7$ dB^2 for the average of three measures from each participant. This variation makes up 52% of the inter-participant variance obtained when averaging the SRTn measurements, suggesting that just over half of the variation in perceptual directional microphone benefit may be explained by measurement errors. The 95% bootstrap confidence interval (CI) (Efron and Tibshirani, 1993) for the proportion of variance is [34%; 78%].

The variation in perceptual directional microphone benefit was not correlated with age ($r = 0.04$, $p = 0.76$) or configuration of hearing loss, calculated as the difference between the average loss across 2, 3, and 4 kHz and the average loss across 0.25, 0.5, and 1 kHz, ($r = -0.18$, $p = 0.18$). Consequently, these parameters were excluded from the further analyses. To determine what other parameters may contribute to the variation in perceptual directional microphone benefit, a forward stepwise multiple regression analysis was performed using the directional benefit scores based on the average SRTn measurements as the dependent variable, and the ASA, SoP, WM, microphone angle, in situ LF 3D AI-DI benefit, and in situ HF 3D AI-DI benefit as independent variables. The analysis revealed a significant model ($F_{3,53} = 12.54$; $p < 0.000001$) that explained 37% of variation in perceptual directional benefit. The parameters in the model included the in situ LF 3D AI-DI benefit, ASA, and microphone angle, suggesting that participants who demonstrated more perceptual benefit from a directional microphone obtained greater physical benefit from the directional microphone at low frequencies, had poorer ASA, and were fitted with the directional microphones pointing more upwards. Table IV lists the regression coefficients, the standard error of the standardised coefficients, the squared multiple correlation, and the significance level for each parameter in the model. While all three parameters seemed to be unique contributors (low R-square values), the in situ LF 3D AI-DI benefit variable contributed the most to the model (high regression coefficients and significance level), which would suggests that the PTA and vent size have some predictive value. On their own the in situ LF 3D AI-DI benefit, PTA and vent size explained 23%, 5%, and 12% of the variation in perceptual directional microphone benefit, respectively. If two participants were excluded, both of whom were identified as outliers due to their residuals exceeding two times the standard deviation (both demonstrated much greater perceptual benefit than predicted from the independent parameters), the same model emerged from the multiple regression analysis, explaining 45% of the variation in perceptual directional benefit. Figure 5 shows how the perceptual directional benefit correlates with each of the three parameters in the model when all data are included.

Discussion

Repeated SRTn measurements, obtained from 59 people fitted with devices set in omnidirectional and fixed directional modes, suggested that half of the inter-participant variation in perceptual directional microphone benefit could be explained by measurement errors associated with the speech-in-noise testing. This result was obtained despite using an automated procedure to measure SRTn that aimed at achieving a target reliability that should result in 95% of the measures of repeated tests falling within a 3.2 dB range. However, across the two microphone modes and repeated measures, the target reliability was not reached in 17% of cases before the maximum number of 32 sentences was expended. Factors that can influence a person’s performance and reliability when measuring SRTn include: head movements that introduce shadowing effects, especially when the hearing aid is in directional mode; list equivalence of the speech test (Dillon, 1982); and practice effects. It should be noted that we observed a small, but significant, practice effect among the repeated SRTn measures obtained with both the omnidirectional ($p = 0.0004$) and the directional ($p = 0.00004$) microphone, as lower SNRs were measured with each microphone mode as the testing progressed (about 0.4 dB/test). This would suggest that the order in which the microphones were tested could contribute to the measurement errors. Small practice effects have previously been observed in SRTn measurements obtained on normal-hearing listeners using similar materials (e.g. Plomp and Mimpen, 1979; Wagener and Brand, 2005; Yund and Woods, 2010), and may be more prominent when using modulated as opposed to stationary background noise (Rhebergen et al., 2008). Overall, these observations suggest that multiple measurements of the SRTn with each microphone mode in a balanced order should be obtained to ensure a reliable indication of how well an individual will perform with a directional microphone. Alternatively, more reliable speech tests for this purpose are needed.

In agreement with previous findings (Ricketts and Mueller, 2000; Jespersen and Olsen, 2003; Wu, 2010; O'Brien et al., unpublished data), this study showed no significant first-order association between perceptual benefit obtained with directional microphones and age, PTA, and configuration of hearing loss. However, previous suggestions that the vent size did not affect perceptual directional microphone benefit was refuted, see below.

Another 37% of variation in perceptual directional microphone benefit was explained in this study by a combination of three parameters: the in situ LF 3D AI-DI, ASA, and microphone angle. The significant contribution by the in situ LF 3D AI-DI benefit measure, which was highly and significantly correlated to vent size, is uncontroversial. It indicates that greater perceptual directional benefit is associated with greater directivity across low frequencies, a finding that agrees with previous studies demonstrating that less benefit, or directivity, was obtained from directional microphones when using open relative to occluded molds (Fabry, 2006; Klemp and Dhar, 2008; Ricketts, 2000). Open fittings have become very popular with hearing aid users due to their ability to alleviate occlusion and the appealing look of the smaller BTEs. However, there is no doubt that the improvement in own-voice quality and appearance compromises the effectiveness of such features as noise reduction and directional microphones, which will be active only at frequencies where the amplified path dominates. Note that while the range of perceptual directional benefit is larger than the range of physical performance measures across the low frequencies, it does correspond nicely with the range of 3D AI-DIs measured across the entire frequency band (cf. Tables II and III).

The relationship between perceptual directional microphone benefit and ASA is harder to explain. It suggests that an improvement in SNR is more important for people with poorer ASA, who therefore show more advantage from the directional microphone. This argument implies that, relative to those with better ASA, those with poorer ASA would either perform more poorly with the omnidirectional microphone or better with the directional microphone. However, there was no significant correlation between ASA and the average SRTn obtained in omni mode ($r = 0.05$, $p = 0.70$) or in directional mode ($r = 0.25$, $p = 0.06$). The average SRTn obtained in either mode was instead highly and significantly correlated with degree of hearing loss ($r = 0.75$, $p < 0.0001$ for omni and $r = 0.70$, $p < 0.0001$ for directional), which is in agreement with previous observations (Jespersen and Olsen, 2003; Killion, 1997; Peters et al., 1998). We further note that while both the ASA and the speech perception test required bottom-up processing, speech perception in noise additionally depends on a top-down process, to make use of contextual cues, that most likely is not activated with the ASA test (e.g. Yoncheva et al., 2010). Finally, it should also be noted that just over one-third of the participants obtained the maximum score for the ASA test, and for this group alone the range of perceptual benefit spans more than 4 dB, or more than 80% of the range of perceptual benefit measured across the entire group of participants. The distribution of scores on a more sensitive ASA test is unknown. However, even if a more sensitive test more strongly confirmed an association of ASA with the perceptual directional microphone benefit in this test population, the direction of the relationship still makes the result difficult to interpret for the reasons outlined above. It would be of interest to explore this factor further. For now, we speculate that there is a physical performance measure that we have not captured in this study which is, coincidentally, better for those with poorer ASA, resulting in the ASA parameter finding its way into the model predicting directional microphone benefit. This seems to be a reasonable assertion in listening situations, such as the one implemented in this experiment, where the target signal comes from a single direction in which the hearing aid wearer is looking. The improvement in SNR offered by a directional microphone is then no different from simply attenuating all the noise sources in the room, which is of equal benefit to every listener, by definition when benefit is expressed as a change in SRTn resulting from the directional microphone. There is much greater likelihood for an interaction between cognitive ability and benefit from directional microphones in complex, multi-talker environments, where rapid and appropriate head turning behaviour (or very smart automatically steered directional microphone beams) are needed to maximize the benefit resulting from directional microphones.

The last parameter to enter the model was the microphone angle, suggesting that more perceptual directional microphone benefit was associated with the microphone pointing slightly upwards. Measurements on KEMAR support this finding, especially for people fitted with the Motion 501 instruments (cf Figure 3), which applied to 66% of the participants. Although the physical advantage is clearly small, it would be emphasized in participants fitted with large vents for whom the physical benefit at low frequencies is reduced to nil. We note that Ricketts (2000) also observed significant effects of microphone angle when the angle exceeded 20° from the horizontal plane, although in his measurements the physical benefit was reduced as elevation increased. The net effect of the microphone port angle likely depends greatly on the detailed polar pattern of the directional microphone and the acoustics of the room in which testing takes place. There is a lot of variation in the relationship between perceptual directional benefit and microphone angle (cf. Figure 5), and the parameter only contributes 4% to the total variation explained by the regression model. Further, given the likely interaction with the acoustic listening environment in particular, we do not recommend that clinicians deliberately fit directional devices so that the microphone orientation is pointing upwards.

While the in situ LF 3D AI-DI benefit contributed strongly to the combination of parameters that predicted the perceptual directional microphone benefit, the in situ HF 3D AI-DI did not make it in to the model. This could be because people are making more use of LF than HF cues, due to either audibility or processing issues, or simply because the spread of 3D AI-DI values was more restricted across the high frequencies (cf. Table II).

The same predictive model emerged if we used the in situ SNR benefit values (both LF and HF) instead of the in situ 3D AI-DI benefit values as the independent variables in the regression analysis, although a slightly smaller percentage of the variation was explained (33%). Overall, we believe our data suggest that variation in perceptual directional microphone benefit not accounted for by measurement error is primarily explained by the physical performance of a directional microphone after the instruments have been fitted. In particular, the frequency range over which the directional microphone is effective, the microphone angle, and the acoustics of the listening environment are factors to consider. These physical parameters are also likely to direct the real-life perceptual benefit from directional microphones, and particularly suggest that the effectiveness of directional microphones across low frequencies should be maximized to achieve optimized performance. Most likely, this factor will have an increasing impact on performance as wireless technology that allows for binaural linkage of dichotic input signals enables the directivity of microphones to increase significantly.

Eleven percentage of the variation in our data remains unexplained. Our results do not entirely exclude an effect of cognition on directional microphone benefit, as only a small set of cognitive tests were applied that did not necessarily capture the effort or cognitive processes associated with utilizing the extra auditory information available as a result of improved SNR. A disorder of auditory processing could also be a candidate, and may be a parameter worth exploring in future studies. However, as measurement error and variation in physical SNR do seem to explain a very large proportion of variability in the perceptual data, any cognitive effects are, for the reasons provided earlier, assumed to be small in more simple test conditions like the one implemented in this study.

Conclusion

Individual variation in perceptual directional microphone benefit is largely explained by measurement error (52%, with a 95% CI from 34% to 78%) and a combination of physical performance factors after being fitted to the individual (37%). Findings specifically emphasize the importance of optimizing the effectiveness of directional microphones across the low frequencies to maximize the perceptual benefit.

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Table I: List of studies that have reported the mean perceptual directional microphone benefit as the difference in SRTn measured with directional and omnidirectional microphones, using sentences presented in diffuse noise, and the benefit range.

Study	N	Device	Speech test (0^0 azimuth)	Noise	Noise azimuths	Comment	Mean benefit (dB)	Benefit range (dB)
Preves et al. (1999)	10	Persona Choice ITE	HINT	Speech shaped	115° and 245°	Avg across equalized and non-equalized responses	2.6	7.6 (-1.1 – 6.5)
Plumford et al. (2000)	24	PiCs AZ	HINT	Speech shaped	72°, 144°, 216°, and 288°	Avg across BTEs and ITEs	4.5	9.3 (0.5 – 9.8)
Ricketts et al (2001)	47	Various, but all tested by all subjects	HINT	Speech shaped cafeteria noise	30°, 105°, 180°, 255°, and 330°	Avg across five hearing aid models, two responses, and two sites.	2.6	14.0 (-3, 11)
Jespersen & Olsen (2003)	32	Canta 770-D	Dantale II	Speech shaped unmodulated	90°, 180°, and 270°	Avg across three categories of degree of hearing loss	3.0	7.0 (-1.0 – 6.0)
Cord et al. (2004)	20	Various (own)	HINT	Speech shaped	90°, 180°, and 270°		2.7	13.9 (-3.4 – 10.5)
Walden et al. (2004)	17	Canta 750-D	HINT	Speech shaped	90°, 180°, and 270°	Avg across three sessions	3.9	10.9 (-1.9 – 9.0)

Peeters et al (2009)	18	Widex Inteo	HINT	Speech shaped	90^0, 180^0, and 270^0	Speech Enhancer disabled	4.0	11.7 (-3.0 – 8.7)
O'Brien et al (unpublished)	26	Prototype	BEST	Uncorrelated speech shaped babble	90^0, 180^0, and 270^0	Avg across open and closed instant-fit tips	3.3	5.9 (0.2 – 6.1)
Wu (2010)	24	Destiny 1200	HINT	Uncorrelated speech-shaped	90^0, 180^0, and 270^0 at two elevations		3.9	6.2 (-0.3 – 5.9)

Table II: The mean, standard deviation, and range of outcomes of cognitive tests and physical performance tests.

Parameter	Mean	Standard deviation	Range
Auditory selective attention (score – max = 13)	9.9	2.9	[4;13]
Speed of processing (score – max = 20)	11.4	3.3	[2;19]
Working memory (score – max = 54)	17.4	4.7	[6;29]
Frequency from which amplified path dominates (Hz)	550.2	216.2	[218;978]
Microphone angle (degrees)	22.6	9.2	[5;41]
In situ BB SNR benefit (dB)	1.76	0.48	[1.07;2.79]
In situ LF SNR benefit (dB)	1.24	0.60	[0.52;2.59]
In situ HF SNR benefit (dB)	3.21	0.56	[2.11;4,80]
In situ BB 3D AI-DI benefit (dB)	3.70	1.07	[1.62;6.41]
In situ LF 3D AI-DI benefit (dB)	2.06	0.83	[0.64;3.76]
In situ HF 3D AI-DI benefit (dB)	1.64	0.43	[0.63;3.31]

Table III: The mean and standard deviation values (shown in brackets) of the SRTn obtained with the omnidirectional (Omni) and directional (Dir) microphones after each of three measurements and averaged across the three measurements. The directional benefit and benefit range for each condition are also shown.

Condition	Omni SRTn (dB)	Dir SRTn (dB)	Benefit (dB)	Benefit range
First measure	1.2 (2.75)	-1.4 (2.64)	2.5 (1.97)	[-2.0;7.2]
Second measure	0.9 (2.63)	-1.9 (2.36)	2.8 (1.46)	[-0.1;6,2]
Third measure	0.4 (2.50)	-2.3 (2.29)	2.7 (1.51)	[-1.5;6.9]
Mean	0.8 (2.50)	-1.9 (2.29)	2.7 (1.16)	[0.3;5.3]

Table IV: The parameters that combined predicted 37% of the variation in perceptual directional microphone benefit listed with the regression coefficients (standardised and raw), standard error (SE) of raw coefficients, squared correlation, and significance level.

Parameter	β	B	SE(B)	R^2	p-level
In situ LF 3D AI-DI benefit (dB)	0.45	0.64	0.15	0.004	0.00006
Auditory selective attention (score)	-0.36	-0.14	0.04	0.003	0.001
Microphone angle (degree)	0.24	0.03	0.01	0.003	0.03

Figure legends

Figure 1: The mean hearing threshold levels for 59 left and right ears. The bars show plus and minus one standard deviation, and the whiskers show minimum and maximum values.

Figure 2: The polar directivity patterns for 0.5 and 2.0 kHz measured for 65 dB SPL random noise on a sample of each of the three test devices; (a) Motion 500 M, (b) Motion 501 P, and (c) Motion 501 SX.

Figure 3: The in situ SNR benefit as a function of microphone port angles as measured on KEMAR across a) low frequencies, b) high frequencies.

Figure 4: The distribution of the perceptual directional microphone benefit scores when considering a) single measurements obtained through three repetitions, and b) the average of three repeated measurements.

Figure 5: The relationship between the perceptual directional microphone benefit and a) the in situ LF 3D AI-DI benefit, b) auditory selective attention, and c) microphone angle.

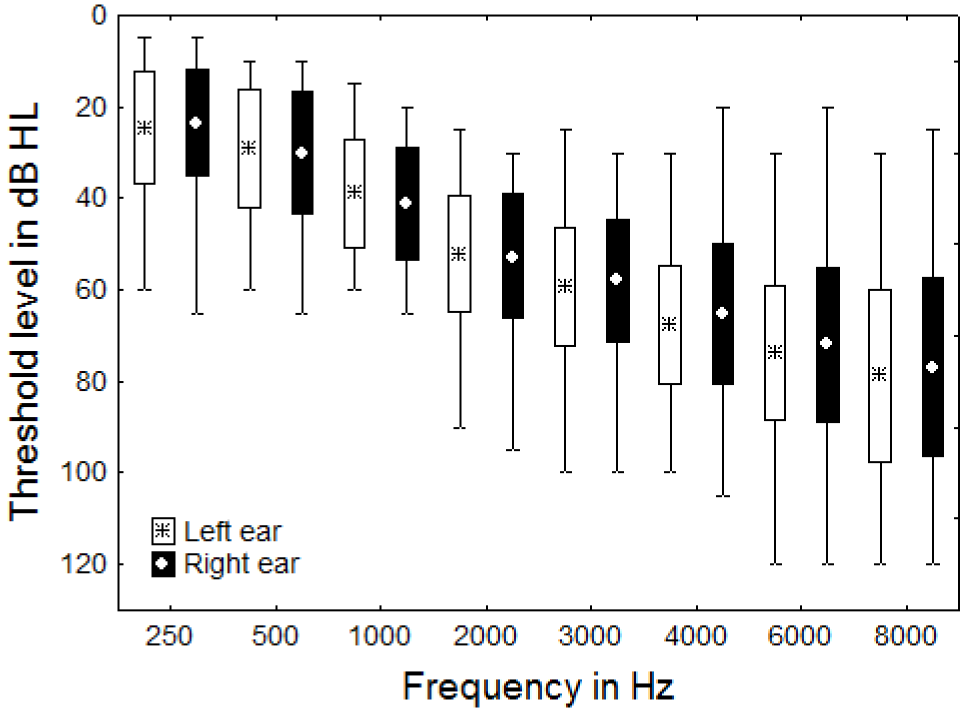
Threshold level in dB HL
0
20
40
60
80
100
120
Left ear
Right ear
250
500
1000
2000
3000
4000
6000
8000
Frequency in Hz

Figure 1

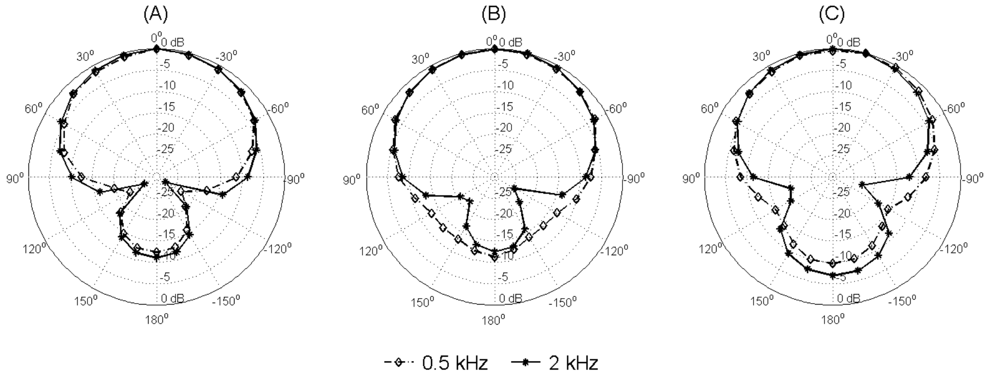
(A)
(B)
(C)
0°
0 dB
-5
-10
-15
-20
-25
30°
-30°
60°
-60°
90°
-90°
120°
-120°
150°
-150°
180°
0.5 kHz
2 kHz

Figure 2

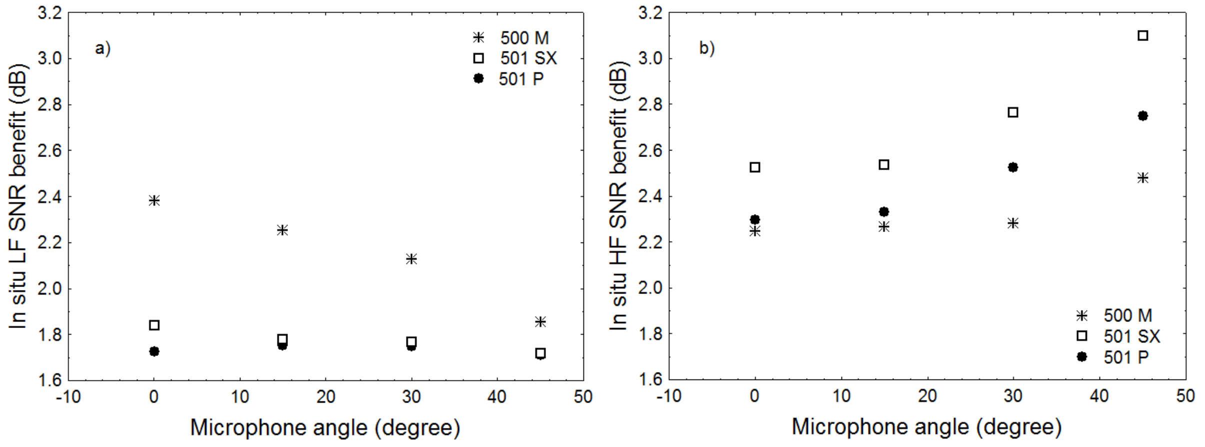
a)
500 M
501 SX
501 P
In situ LF SNR benefit (dB)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
-10
0
10
20
30
40
50
Microphone angle (degree)
b)
In situ HF SNR benefit (dB)
500 M
501 SX
501 P
Microphone angle (degree)

Figure 3

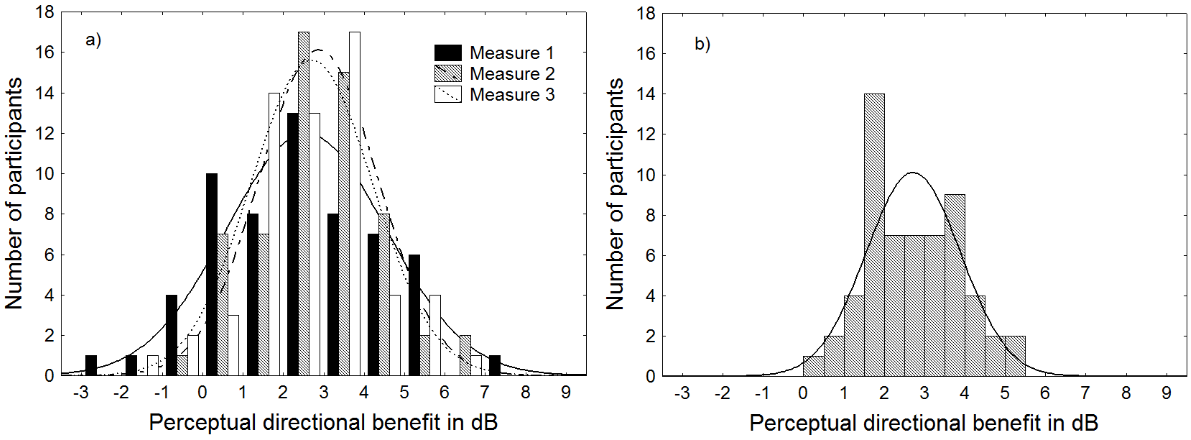
a)
Measure 1
Measure 2
Measure 3
Number of participants
Perceptual directional benefit in dB
0
2
4
6
8
10
12
14
16
18
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
b)

Figure 4

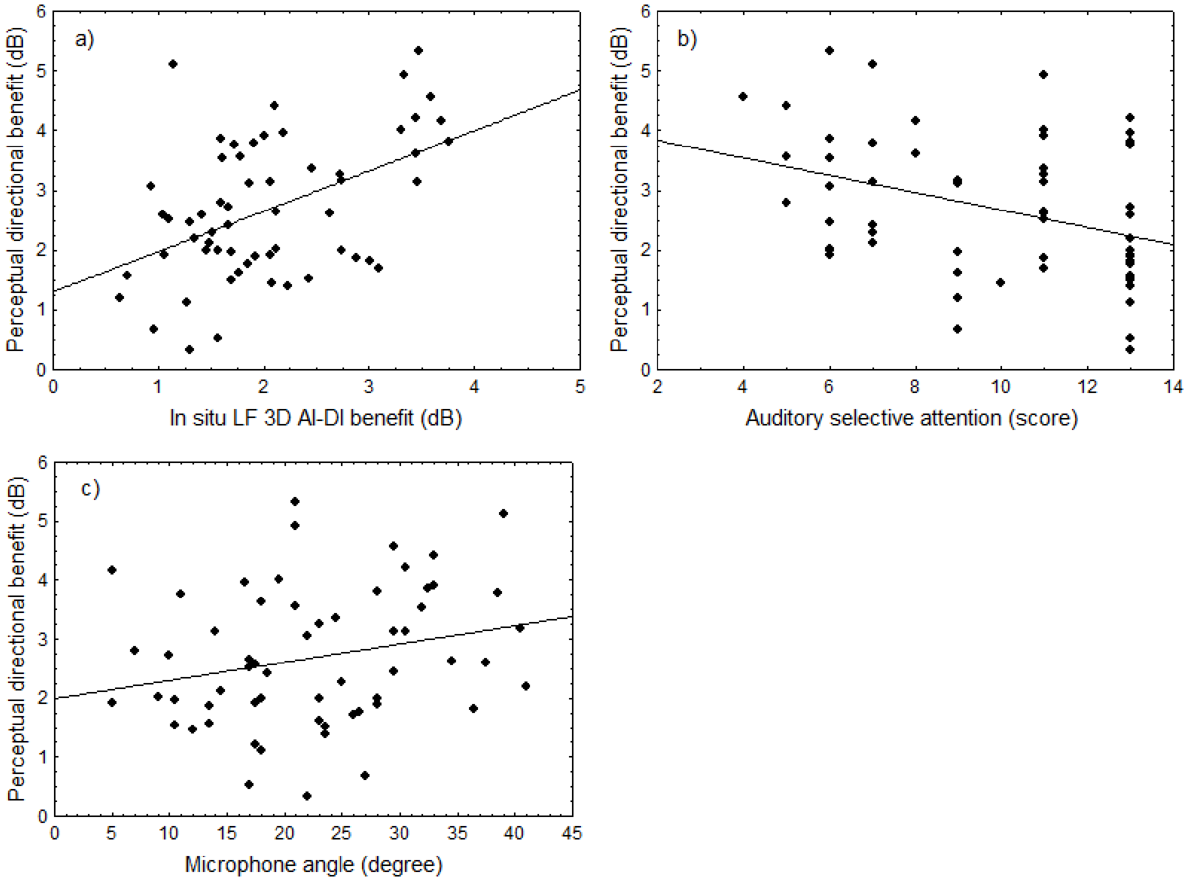
a)
Perceptual directional benefit (dB)
0
1
2
3
4
5
6
0
1
2
3
4
5
In situ LF 3D AI-DI benefit (dB)
b)
Perceptual directional benefit (dB)
0
1
2
3
4
5
6
2
4
6
8
10
12
14
Auditory selective attention (score)
c)
Perceptual directional benefit (dB)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
Microphone angle (degree)

Figure 5