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The speech intelligibility benefit of a unilateral wireless system for hearing impaired adults

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Abstract

Objective—This study measured the effects of two previously untested practical considerations - venting and transmission delays - on speech intelligibility in a simulated unilateral wireless system, where a target signal in background noise was transmitted wirelessly to the hearing-impaired (HI) listener.

Design—Speech reception thresholds (SRTs) relative to the signal-to-noise ratio (SNR) were measured by varying the surrounding babble noise level. The target signal was presented at 0° azimuth in the soundfield and unilaterally via an insert earphone, using open and closed fittings with simulated-wireless delays ranging between 0-160 ms. SRTs were also measured unaided and with participants' current hearing aid(s).

Study sample—Thirty-three mild-to-moderate sensorineural HI adults participated in the experiment.

Results—For an open fitting, the results showed a 5-dB SNR benefit in SRT compared to unaided performance at shorter delays. For a closed fitting, the majority of participants could accurately recognize speech below -20 dB SNR across delays.

Conclusions—These results highlight the efficacy of wireless systems with HI adults. Speech-intelligibility benefits are affected by transmission delays only when the delay is greater than 40 ms and the coupling is vented.

Keywords

Hearing impairment; speech intelligibility; wireless technology

1. INTRODUCTION

Speech understanding in noise is a significant problem for hearing impaired (HI) listeners (Harkins & Tucker, 2007) for which hearing aids can only provide partial benefit (e.g., Marrone et al., 2008). The speech understanding in noise problem would be reduced if the listener could be given a signal without any of the environmental noise. One way to achieve this is to transmit a wireless signal to HI listeners in a noisy setting through a system where the talker has a microphone transmitter and the listener has a wireless-receiver embedded device. There are currently several wireless systems based on differing technologies, including magnetic induction (e.g., telecoil), frequency-modulation (FM) and Bluetooth (a standard digital wireless encoding protocol). All allow a wireless signal to arrive at one or

both ears with reduced environmental noise, though they vary in how much of the noisy airborne signal is allowed to mix with the transmitted wireless signal through different couplings to the ear. These systems can also vary in the amount of transmission delay (i.e., the time to encode, send and decode) added to the transmitted signal: FM transmission is near instantaneous, but high-bandwidth Bluetooth-to-nearfield-magnetic-induction transmission can give a delay of over 100 ms.

Previous research into the benefits of a wireless FM system has been mostly limited to HI children (e.g., Crandell & Smaldino, 2001; Hawkins, 1984; Pittman et al., 1999). These studies found that a classroom FM system provided a significant advantage to conventional hearing amplification with or without directional microphone technology in noisy environments. When the wireless system output is mixed with the hearing aid microphone output, which allows the child to hear their environment as well as the transmitted signal, the results are mixed. Hawkins (1984) found performance with the combination of FM and hearing aid microphone signals to be closer to aided only performance than FM only performance in an adaptive spondee recognition task with noise directly behind the participant. In a nonsense syllable identification task, Pittman et al. (1999) found no significant difference between mixing hearing aid and FM signals in both ears, with the hearing aid signal mixed 10-dB lower than the FM signal, and presenting FM in one ear and hearing aid output to the other with noise to the left and right of the participant. Nevertheless, these studies, along with other studies examining FM use for children (e.g., Crandell & Smaldino, 2001; Crandell et al., 2002; Kreisman & Crandell, 2003), all agree that there is a large benefit for a classroom FM system, even if they do not agree on the amount of benefit when the FM signal is mixed with another signal, such as with a hearing aid.

There have been two studies with HI adults that have examined the benefit of hearing aid FM systems. Fabry (1994) found that for five moderate-to-severe HI adults using a Phonic Ear device with the other ear occluded, the FM signal alone provided a substantial (9-10 dB) speech intelligibility benefit compared to the hearing aid microphone signal or combination of signals. If only the high frequency portion of the hearing-aid signal was mixed with the wireless signal, the benefit increased, but was still significantly 3-dB less than FM alone. Lewis et al. (2004) tested the efficacy of a bilaterally fit Phonak hearing aid FM system with mild-to-severe HI adults; they found speech reception thresholds (SRTs) in noise improved 15-20 dB for FM input compared to omnidirectional hearing aid input. These studies illustrate the potential benefit of wireless systems with HI adults, but have only tested specific systems (i.e., particular FM enabled hearing aids by Phonic Ear and Phonak). There is no generalisable evidence of the benefit across different hearing aids or wireless technologies.

Given the variability in transmission fidelity within just FM systems (e.g., frequency response, distortion, delay; Thibodeau & Saucedo, 1991), a generic wireless system needs to be assessed across (a) different transmission methods (e.g., dedicated FM, telecoil, Bluetooth) which incur different delays, and (b) different device types (e.g., hearing aids, amplified headsets) which offer different couplings with the ear, from fully occluding moulds to fully open fittings. Results from a recent comparison of the transmission delay in currently available wireless hearing aids varied from 18 ms for a 2.4 GHz FM system to 60 and 130 ms for Bluetooth-to-nearfield-induction systems (Groth, 2010). Such delays will be of importance if there is any mix of the wirelessly transmitted signal with the acoustic signal. Stone, Moore and colleagues found maximum tolerable delays before listeners rated the signals as annoying for bilaterally fit hearing aids to be 5-6 ms with an open fitting (Stone et al., 2008), and 9 ms with a closed fitting (Stone & Moore, 2003). Furthermore, they found that speech intelligibility, measured with a nonsense syllable identification task,

was negatively affected by delays greater than 15 ms with a closed fitting (Stone & Moore, 2003). It is worth considering, however, that Haas (1972) earlier had found a single echo of a speech signal to increase the perceived level of the speech without decreasing speech intelligibility with delays up to 30 ms. With an open fitting, there would be both an acoustic noisy signal and a delayed, wirelessly transmitted signal, but there is no clear indication from previous studies how a delayed wirelessly transmitted signal in an open fitting would be different from the expected speech intelligibility benefit of a closed fit wireless system (cf. Fabry, 1994; Lewis et al., 2004). Given the range of wireless systems currently available, it is therefore vital to know the role of delay as well as venting in the potential benefit of wireless systems to temper expectations when fitting wireless ready devices.

To avoid the confounding of different compression and gain-prescription schemes, the present study was limited to mild-to-moderate HI participants, who can avail themselves of more choices in hearing assistance. The present study was also limited to testing unilaterally, so that one ear receives the airborne signal and noise and the other ear receives the simulated wireless signal along with some of the airborne signal and noise determined by the type of coupler. Despite the benefit often received with a bilateral fitting (for exceptions, see Köbler et al., 2010), policy in the United Kingdom, for example, has only included bilateral fitting recommendations since 2005, so many patients have not been offered bilateral provision. The prevalence of unilateral fittings was evident in the current study; of the 21 hearing-aid wearers recruited to participate, all had hearing loss in both ears, but only one was fit with bilateral hearing aids.

The current study examined the extent of benefit of an “ideal” analogue of a wireless system by assessing speech intelligibility in a noisy environment across different couplers and delays. A sentence was presented from a loudspeaker, and a wired insert earphone presented a copy of the sentence. To make the current study generalisable to differing technologies, the copy of the signal was presented (a) with delays ranging from those found in hearing aids (0-10 ms) to the longer delays (80-160 ms) found in Bluetooth-to-nearfield-induction or FM systems, and (b) with unvented (closed) and fully vented (open) couplers, representing traditional FM earplugs (closed) and current trends in open-fit hearing aids and Bluetooth earpieces (open). Note that this method is a simulation of a generic wireless system, not an instantiation of any specific one; we therefore refer to the delay as “simulated transmission delay.” The results from this study therefore do not describe the results of a particular wireless system, but rather prescribe the potential speech intelligibility benefit for wireless systems utilizing different transmission systems and venting options.

2. METHODS

The current study tested a simulated unilateral wireless system where the target speech signal was presented through a monaural insert earphone as well as from a loudspeaker in front of the listener in surrounding babble noise from five loudspeakers. Since the level of the signal in any real wireless system would likely remain constant – the talker would speak into their microphone at a conversational level – the level of the babble noise, not the target speech, was adaptively varied to estimate SRTs. The simulated wireless signal was varied in delay from 0-160 ms in exponential steps (i.e., 0, 5, 10, 20, 40, 80 and 160 ms) and presented through both an open and closed coupler. To allow benefit to be calculated, these results were compared with two control conditions: unaided and with their current hearing aids.

2.1. Participants

Forty-two participants (21 female, 21 male) were recruited from the pool of HI patients available to the Institute of Hearing Research, sourced from attendees at clinics of the local

hospitals by postal survey. Pure-tone thresholds were assessed using the modified Hughson-Westlake method (British Society of Audiology, 1981). Data from nine participants were excluded based either on (a) type or (b) magnitude of loss: (a) three participants had primarily conductive hearing losses; (b) six other participants had four-frequency pure-tone threshold averages (4FAs) greater than 50 dB HL, and had difficulties correctly recalling the target sentences in quiet (see Procedure section below). As shown in Figure 1, (sensorineural) hearing losses of the remaining 33 participants (17 female, 16 male), aged 34-75 years (median 67 years), varied from normal-to-mild to mild-to-moderate. Twenty-one participants wore hearing aids at the time of their visit: 10 were unilaterally fit in the left ear, 10 in the right ear, and one bilaterally. Two of the 20 unilaterally aided participants were wearing an aid on their worse ear based on 4FA. These participants were tested with their own hearing aids, which all had been clinically fit and adjusted at least six months beforehand. All hearing aids were worn in their default program with an omnidirectional microphone pattern. For comparison purposes, a small group of five participants with normal hearing (NH) based on pure-tone thresholds being less than 25 dB HL from 250-4000 Hz were recruited from the employees of the Institute of Hearing Research to run the same procedure unaided.

2.2. Apparatus

Participants were seated in a sound-dampened room ($2.5 \times 4.4 \times 2.5$ m) in the middle of a circular six-loudspeaker array with a radius of 0.9 m and inter-loudspeaker spacing of 60 degrees (see Figure 2). The stimuli were presented from an outboard signal processor through a D/A converter (Fostex VC-8) and attenuator (Behringer Ultralink) to powered (built-in amplifier) loudspeakers (Phonic 207). The loudspeakers were all calibrated prior to each session to within ± 1 dB SPL at 1000 Hz for pink noise presented at 80 dB SPL. Target sentences were presented from the loudspeaker at 0° azimuth to the participant. Babble was presented from loudspeakers at 60, 120, 180, 240 and 300° . The height of the fixed chair was adjusted so that the cone of the loudspeakers was at 0° elevation relative to the participant's ear canal. Participant responses were monitored with a wireless microphone.

For the simulated wireless system, target sentences were also presented at a long term average A-weighted level of 70 dB SPL to the participant via an insert earphone [Etymotic Research (ER) 3A] using either a foam plug (ER-14) or an open dome (Siemens Centra dome) for closed- and open-coupler conditions, respectively. Insertion depth, measured at the entrance to the ear canal, for both coupler types was kept constant across all participants through visual confirmation. To compare with aided results, inserts were placed on the aided ear for those who were fit unilaterally with hearing aids (10 left ear, 10 right ear), on the better (right) ear for the one fit bilaterally and the better ear based on average pure-tone thresholds for those participants who did not wear hearing aids (7 left ear, 5 right ear). Two of the unilaterally aided participants wore hearing aids on their worse (based on 4FA) ear, and, therefore, were wearing the coupler on their worse ear; their results were not significantly different from the remaining participants.

2.3. Stimuli

The target speech stimuli were sentences from the Bamford-Kowal-Bench (BKB) corpus (Bench et al., 1979) spoken by a single English female talker. Sentences were presented in consecutive order to maintain the phonetic balance of the original corpus when estimating thresholds; no sentence was presented twice to the same participant. The target speech was presented at a fixed long-term A-weighted average level of 70 dB SPL. The noise maskers were concatenations of different sentences of the same male talker from the Adaptive Sentence List (ASL) corpus (MacLeod & Summerfield, 1990); that is, each loudspeaker emitting noise presented single male-talker speech, resulting in spatially distributed babble.

The babble began 500 ms before the onset of target sentences and was gated off 500 ms after the target sentence finished. The babble level was adaptively adjusted. For the simulated-wireless signals played through an open and closed coupler, delays of 0-160 ms were added to the signals that included the propagation delay of the acoustic signal (2.6 ms, based on the speed of sound at room temperature). Due to time constraints, not all delays could be tested with all participants: for the first 11 participants, the simulated transmission delays were 0, 5 and 10 ms; for next 11 participants, the delays were 10, 20 and 40 ms; for the remaining 11 participants, the delays were 40, 80 and 160 ms. Thus, there were 11 participants tested at 0, 5, 20, 80 and 160 ms, and 22 participants tested at 10 and 40 ms.

2.4. Procedure

SRTs were measured using an adaptive tracking procedure. On each trial, participants were presented with a target sentence in babble, and asked to repeat back as much of the target sentence as possible. Correct responses were defined as complete reiteration of the target sentence, allowing for changes to articles and dialect-based pluralisation (e.g., the adding of s to non-possessive pronouns). The signal-to-noise ratio (SNR) was varied by adjusting the babble level using a two-up/one-down rule, estimating 71% correct threshold (Levitt, 1971). The starting SNR was randomly selected from -3 to +3 in 1-dB increments. The SNR was adjusted in 4-dB steps for the first two reversals, then 2-dB steps for two reversals, then finally in 1-dB steps for four reversals. The SRT estimates were based on the average of the SNRs at the last four (1-dB step) reversals. For all mean SRT results, an analysis of variance was conducted with pairwise comparisons using the Games-Howell correction for unequal sample sizes (Games & Howell, 1976).

After participants were first instructed on the task, an initial practice was given with an unused list (16 sentences) of the target speech presented in quiet. Testing then began with either open or closed simulated wireless signal condition blocks. The order of simulated transmission delays were randomized within each block. Participants then were tested aided (if they wore hearing aids) and unaided in randomized order, followed by the other (closed or open) simulated wireless signal block. While the uncoupled blocks always were in between the coupled blocks, the order of open- and closed-coupler blocks, as well as unaided and aided, were counterbalanced across participants. The complete session, including initial audiometric testing, lasted approximately 60-90 minutes.

Because the level of the babble noise was adaptively varied, the better a participant performed the higher the noise level became. To avoid a very intense masker, the maximum level of the babble was limited to be 20 dB more than the target. If the listener's responses indicated that they could easily recognise the targets at a SNR of -20 dB by continuous correct responses at lower SNRs, then the adaptive track was stopped and it was inferred that the SRT would have been less than -20 dB SNR.

2.5. Acoustic analysis

To further investigate the effects of venting on wireless signal benefit, the levels of the noises and signal were measured. Thirty seconds of concatenated signal and noise stimuli were presented sequentially in the soundfield and also with the signal presented with open and closed-couplers to a Knowles Electronics Manikin for Acoustic Research (KEMAR) mounted with an artificial pinna, a Zwislocki coupler and 1/2-inch reference microphone (Bruel & Kjaer 4189). Signal and noise were both presented at average A-weighted levels of 70 dB SPL (i.e., 0 dB SNR). The long-term average A-weighted levels at the canal were measured and recorded with a sound level meter (Bruel & Kjaer 2260).

3. RESULTS

Figure 3 reports mean SRTs for all the conditions. The filled symbols plot the results from the NH participants (squares) and unaided and aided conditions for the HI participants (triangles). The HI listeners required a 5-dB significantly higher SNR ($p < .05$) for SRTs than the NH listeners, but there was no significant difference ($p > .05$) between their mean unaided or aided performance (-0.2 and 1.7 dB SNR, respectively).

The open symbols plot the results from the open-coupler conditions. An analysis of variance of mean open-coupler SRTs revealed a significant effect of (simulated) transmission delay [$F(6, 92) = 3.1, p < .01$]. The mean SRTs with an open coupler were relatively constant across the delays of 0-20 ms at about -5.5 dB SNR, closely matching NH performance and significantly ($p < .01$) less (better) than unaided and aided performance. The SRTs increased with transmission delays greater than 20 ms and were not significantly different ($p > .05$) from mean unaided performance at the longest delays of 80 and 160 ms. At the longest delay tested, 160 ms, mean open-coupler performance was significantly poorer ($p < .05$) than mean open-coupler performance at shorter delays (0-20 ms) and not significantly different ($p > .05$) than HI control conditions.

The letters plot the results from the closed-coupler conditions. Each letter plots the SRT from each participant. If no letter is shown then that participant's SRT was less than -20 dB SNR for that transmission delay; the fraction reports the number of such participants, as the number of participants varied for each delay condition as a by-product of the design (i.e., $n = 22$ at 10 and 40 ms; $n = 11$ at 0, 5, 20, 80 and 160 ms). In general, we found that the majority of participants (64-73%) gave SRTs less than -20 dB across delays, except at 20-ms transmission delay, where only 45% of the participants performed below -20 dB SNR. Overall, open-coupler performance was substantially poorer than closed-coupler performance at all delays. For 88 of the 99 total threshold estimates, closed-coupler SRTs were at least 5 dB SNR better than open-coupler SRTs.

3.1. Correlations

As shown in Figure 4a and 4b, unaided SRTs were well correlated with both average audiometric thresholds (Pearson product-moment correlation $r = .47, p < .01$) and aided SRTs ($r = .67, p < .005$). Note that the majority of participants performed worse with their hearing aids than without, in that the majority of points are above the 1:1 diagonal (Figure 4b). The audiometric thresholds were not significantly correlated, however, with performance with an open or closed coupler ($p > .05$), nor was age significantly correlated with any measure ($p > .05$). For the closed-coupler conditions, separating participants whose SRT was less than -20 dB SNR from the others, revealed no significant differences in 4FAs (34.1 and 38.9 dB HL, respectively) or age (the mean age was 65 years in both groups). That is, there was no clear predictor of performance with an open or closed coupler.

3.2. Acoustic analysis

Long-term average A-weighted levels were measured for stimuli and noise presented sequentially at 70 dB SPL, corresponding to 0 dB SNR, without a coupler. With an open coupler, the measured stimulus and noise levels were 65.9 and 64.3 dB SPL, corresponding to +1.6 dB SNR benefit. With a closed coupler, the measured stimulus and noise levels were 65.1 dB and 34.8 dB SPL, corresponding to +30.3 dB SNR benefit. That is, the mean SRTs with an open coupler (in one ear) at delays of 0-20 ms were on average 5.3 dB lower (better) than unaided performance, which is approximately 3.7 dB better than expected from acoustic measurement of speech and noise levels at the open-coupled ear. Closed-coupler

SRTs exceeded -20 dB SNR for most participants, which would be expected from the measured closed-coupler SNR.

4. DISCUSSION

This experiment has demonstrated a clear speech intelligibility benefit for an idealized unilateral wireless system compared to performance with or without mild-to-moderate HI listeners' hearing aids. This benefit was resistant to delay in the wireless system up to 20 ms. The benefit was significant regardless of the coupler used to deliver the simulated-wireless signal to the ear, but was much greater when a closed coupler was used.

The 5-dB SNR difference between NH and HI unaided performance corroborates previous findings on mild-to-moderate HI listeners having increased difficulty in noisy situations; Humes and Roberts (1990), for example, found nonsense-syllable recognition in noise to be roughly 40% worse for mild-to-moderate HI than NH listeners. The significant correlation between audiometric threshold and unaided performance indicates that audibility was a possible factor in individual performance without hearing aids (*cf. ibid.*; Smoorenburg, 1992; Humes, 1996). As part of the inclusion process, however, all participants were required to be able to accurately recognize sentences in quiet. The significant correlation between unaided and aided performance shows that non-audibility issues in speech-in-noise performance, such as exacerbated masking thresholds from modulated noise such as the babble used in the current study, were also a factor (Takahashi & Bacon, 1992). There was no significant difference between unaided and aided performance, but for two thirds of the aided participants, their aided SRTs were poorer than their unaided SRTs (i.e., above the diagonal in Figure 4b). Recent studies of speech intelligibility have also shown no significant differences between unaided and aided (omnidirectional-microphone) conditions (e.g., Ricketts & Dhar, 1999; Walden et al., 2000; Marrone et al., 2008; Valente & Mispagel, 2008) with individual aided performance often poorer than unaided (Marrone et al., 2008).

The speech intelligibility benefit with a closed coupler was dramatic: the majority of participants received more than 20 dB of benefit compared to unaided or aided performance. The benefit of a closed coupler was also unaffected by delay, except at 20 ms, where the majority of listeners (55%) did not exceed the ceiling set by the apparatus. Stone and Moore (2003) found low frequency delays greater than 15 ms to their maximum tested delay of 26.5 ms to degrade syllable identification, but that effect was relatively small and their delays were presented to both left and right ears. If 20 ms was a more deleterious delay than shorter or longer delays for sentence recognition in general, then it should have been reflected in open-coupler results, which it was not. It is possible that this is simply an anomaly caused by the small number of participants ($n = 11$) tested at this delay. As both the noise and airborne signal were attenuated (-30 dB) in the coupled ear, most participants were able to ignore the other ear across ears, and use the better-audibility, better-SNR (coupled) ear for speech recognition. Based strictly on monaural, better-ear listening, the closed-coupler results for the majority of participants were predicted from the acoustic measurements (*cf. Zurek, 1993*).

Speech intelligibility benefit with an open coupler was much less than with a closed coupler, but much more at shorter simulated transmission delays (approx. 5 dB SNR) than predicted from acoustic measurements of speech and babble levels at the coupled ear (approx. 1 dB SNR). That is, having a simulated wireless signal presented to one ear, with most of the noise leaking through the fully open coupler provided more than a simple, modest boost to the signal level. This could be a demonstration of the speech intelligibility gain shown by Haas (1972) for a single echo, as the perceived level in the coupled ear could have been

increased by the simulated wireless signal effectively being an echo, with the perceived loudness inversely related to the delay of the echo (Haas, 1972). If this was an example of Haas' finding, creating a louder signal and therefore a greater SNR, then SRTs should have decreased from no delay to 5-20 ms delays, which was not the case. Despite the modest increase in SNR, the open-coupler condition provided a more audible signal, including higher frequencies where the participants had greater hearing loss and are particularly important for speech perception. No significant benefit was found when the simulated-wireless signal was presented to the ear 80 or 160 ms after the airborne signal, indicating that longer delays were disrupting the information from the earlier arriving airborne signal. Given that full-bandwidth Bluetooth delays have been measured at 130 ms in currently available hearing aids (Groth, 2010), it is important to consider the potential problems – loss of speech-intelligibility benefit – patients may encounter when using these devices for wireless communication with an open fitting.

The results of this experiment indicate the extent of benefit one can expect from any actual wireless system. With a closed coupler, speech intelligibility benefit should exceed 20 dB SNR. With an open coupler, speech intelligibility benefit for dedicated FM systems and telecoil should be approximately 5 dB SNR; for Bluetooth based systems, care must be taken to ensure that the system delays are less than 80 ms to achieve the same amount of benefit. That is, the wireless system should only present the highest fidelity signal possible without incurring long delays. In such a system, there would most likely be noise leaking into the microphone worn by the listener, reducing potential benefit. The current study tested only a mild-to-moderate population at a fixed level without individualised gain; if individualised gain was applied to the wirelessly transmitted signal, speech intelligibility benefit could increase with audibility. It is unclear how results would differ with a more severe HI population, though with proper individualised gain ensuring audibility of the simulated wireless signal, the extent of benefit should not decrease. This study was limited to a unilateral simulated wireless system; while a closed-coupler bilateral wireless system would present issues for the wearer having no environmental sound input, the potential binaural benefits of an open-coupler bilateral wireless system warrant further study. With current trends toward open fittings for more patients, the current data shows that these patients can still benefit from wireless connectivity from an external source to their hearing aids despite background noise entering their open-ear canal.

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LIST OF ABBREVIATIONS

4FA	Four-frequency (pure-tone) average
ASL	Adaptive Sentence List
BKB	Banford-Kowal-Bench
ER	Etymotic Research
FM	frequency modulation
HI	hearing impaired

HL	hearing loss
KEMAR	Knowles electronics manikin for acoustic research
NH	normal hearing
SNR	signal-to-noise ratio
SRT	speech reception threshold

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Figure 1.
Mean pure-tone audiometric thresholds as a function of frequency for left and right ears showing ± 1 standard deviation.

Figure 2.

Schematic of six-loudspeaker array. The target speech signal was presented in front (0°) and male-talker babble was presented from five loudspeakers surrounding the listener at 60° , 120° , 180° , 240° and 300° . A simulated wireless copy of the target signal was presented via an insert earphone (both open/vented and closed/unvented) to one ear. The simulated wireless signal was delayed from 0-160 ms to simulate transmission delays.

Figure 3.

Mean speech reception thresholds (SRTs) for unaided and aided listening as well as with a simulated wireless signal presented unilaterally at transmission delays of 0 (no delay) to 160 ms. Mean normal hearing (square), unaided (downward triangle), aided (upward triangle) and open-coupler SRTs (open circles) are shown with 95% between subject confidence intervals. Closed-coupler SRTs are shown by individual (letters A-Q) and at the bottom by the number of listeners whose SRT exceeded system hardware limitations (-20 dB SNR).

Figure 4.

Left panel (a) shows individual unaided speech reception thresholds (SRTs) as a function of better ear four frequency average (4FA) pure-tone audiometric thresholds. Right panel (b) shows individual aided SRTs as a function of unaided SRTs. Lines show linear regressions; correlation coefficients (both significant, 4FA vs. unaided SRT at the $p < .01$ level, and unaided vs. aided SRT at the $p < .005$ level) are given in the upper right and lower right corners of each panel, respectively.