Published in final edited form as:
Ear Hear. ; 42(3): 492–505. doi:10.1097/AUD.0000000000000970.

Effects of directionality, compression, and working memory on speech recognition

Rallapalli Varsha[1], **Gregory Ellis**[1], **Pamela Souza**[1,2]

[1]Department of Communication Sciences & Disorders, Northwestern University, Evanston, Illinois, USA

[2]Knowles Hearing Center, Northwestern University, Evanston, Illinois, USA

Abstract

Objectives: Previous research has shown that the association between hearing aid processed speech recognition and individual working memory ability becomes stronger in more challenging conditions (e.g., higher background noise levels) and with stronger hearing aid processing (e.g., fast-acting wide dynamic range compression, WDRC). To date, studies have assumed omnidirectional microphone settings and collocated speech and noise conditions to study such relationships. Such conditions fail to recognize that most hearing aids are fit with directional processing that may improve the signal-to-noise ratio (SNR) and speech recognition in spatially-separated speech and noise conditions. Here, we considered the possibility that directional processing may reduce the signal distortion arising from fast-acting WDRC and in turn influence the relationship between working memory ability and speech recognition with WDRC-processing. The combined effects of hearing aid processing (WDRC and directionality) and SNR were quantified using a signal modification metric (cepstral correlation) which measures temporal envelope changes in the processed signal with respect to a linearly amplified reference. It was hypothesized that there will be a weaker association between working memory ability and speech recognition for hearing aid processing conditions that result in overall less signal modification (i.e., fewer changes to the processed envelope).

Design: Twenty-three hearing-impaired individuals with bilateral, mild to moderately-severe sensorineural hearing loss participated in the study. Participants were fit with a commercially available hearing aid and signal processing was varied in two dimensions: i) Directionality (omnidirectional [OMNI] versus fixed-directional [DIR]), and ii) WDRC speed (fast-acting [FAST] versus slow-acting [SLOW]). Sentence recognition in spatially-separated multi-talker babble was measured across a range of SNRs: 0 dB, 5 dB, 10 dB, and quiet. Cumulative signal modification was measured with individualized hearing aid settings, for all experimental conditions. A linear mixed-effects model was used to determine the relationship between speech recognition, working memory ability, and cumulative signal modification.

Results: Signal modification results showed a complex relationship between directionality and WDRC speed, that varied by SNR. At 0 and 5 dB SNRs, signal modification was lower for SLOW

Address correspondence to Varsha Rallapalli, Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208. varsha.rallapalli@northwestern.edu.

All authors contributed equally to this work. The authors have no conflicts of interest to disclose.

than FAST regardless of directionality. However, at 10 dB SNR and in the DIR listening condition, there was no signal modification difference between FAST and SLOW. Consistent with previous studies, the association of speech recognition in noise with working memory ability depended on the level of signal modification. Contrary to the hypothesis above, however, there was a significant association of speech recognition with working memory only at lower levels of signal modification, and speech recognition increased at a faster rate for individuals with better working memory as signal modification decreased with DIR and SLOW.

Conclusions: This research suggests that working memory ability remains a significant predictor of speech recognition when WDRC and directionality are applied. Our findings revealed that directional processing can reduce the detrimental effect of fast-acting WDRC on speech cues at higher SNRs, which affects speech recognition ability. Contrary to some previous research, this study showed that individuals with better working memory ability benefitted more from a decrease in signal modification than individuals with poorer working memory ability.

INTRODUCTION

Hearing aid processing modifies the incoming signal to provide increased access to speech information for hearing-impaired listeners. However, some modifications can have unintended negative consequences such as the distortion of certain speech cues (e.g., Jenstad & Souza, 2005; McDermott, 2011; Kim & Loizou, 2011), and reduced speech intelligibility depending on the processing parameters and the listener's sensitivity to such modifications (e.g., Arehart et al., 2015; Reinhart et al., 2019; Souza et al., 2015; 2019). Previous research has shown that speech intelligibility in noise is strongly associated with the amount of signal modification quantified at the hearing aid output (Arehart et al., 2013; Arehart et al., 2015; Neher, 2014; Souza et al., 2015; 2019). Therefore, rather than evaluate the hearing aid algorithms in terms of individual processing parameters, the present study focuses on listener responses to the combined signal modification created by two core hearing aid features: wide dynamic range compression (WDRC) and directionality. Signal modification is quantified using an acoustic metric (cepstral correlation; Kates et al., 2014) that incorporates the effects of an impaired peripheral auditory system (Kates, 2013), and compares the time-frequency modulation patterns of a hearing aid processed signal in noise to a linearly amplified reference signal in quiet. Thus, signal modification in this study refers to the cumulative temporal envelope changes as a result of the hearing aid processing parameters, the individual audiogram, and the listening environment, including relative speech and noise levels. Greater signal modification occurs when the temporal envelope modulations in the processed signal deviate further away from the modulations in the reference signal.

Wide dynamic range compression (WDRC)

WDRC is a widely available hearing aid processing strategy designed to restore the audibility of low-intensity sounds while maintaining listening comfort for high-intensity sounds. However, using WDRC may increase signal audibility while also increasing signal distortion due to the compression speed, particularly the release time. Fast-acting WDRC, which is characterized by release times shorter than 250 ms, can respond to rapidly changing input levels in the signal. Increasing gain to a greater extent for low-intensity than for high-intensity phonemes results in overall improvements in speech audibility. In doing so, the fast-acting compressor can introduce significant distortions (i.e., modifications) of the speech signal and degrade speech intelligibility (Rhebergen, et al., 2009). Specifically, fast-acting WDRC can: reduce the natural peak-to-valley intensity differences between consonants and vowels (Ellison et al., 2003), amplify interfering noise in the valleys of speech (Naylor & Johannesson, 2009; Souza et al., 2006; Alexander & Masterson, 2015; Rhebergen et al., 2017), and introduce temporal envelope distortions (e.g., Jenstad & Souza, 2005; Stone & Moore, 2007; 2008). A complimentary set of effects on speech cues have been reported for slow-acting WDRC, which is characterized by release times > 250 ms. With slow-acting WDRC, envelope information in the signal is preserved but audibility may be inadequate for low-intensity portions of the signal, especially in the presence of background noise (Kowalewski et al., 2018). This balance between improved audibility and signal modification with different WDRC speeds has implications for speech recognition outcomes for hearing-impaired listeners. For example, studies have shown that fast-acting WDRC improves speech recognition at low input levels (Henning & Bentler, 2008), but once audibility is achieved at average and high input levels, fast-acting WDRC degrades speech recognition (e.g, Davies-Venn et al., 2009; Souza & Turner, 1998). This effect is most pronounced for listeners who are presumed to depend on the integrity of temporal envelope information (e.g., Stone & Moore, 2007; 2008) such as individuals with greater degrees of hearing loss (Davies-Venn & Souza, 2014) or with poorer working memory (e.g., Souza et al., 2015).

Directionality

Hearing aid directionality is a processing strategy available for communication in noise in most modern devices (Rallapalli et al., 2018). Directional processing incorporates multiple microphones with a variety of sensitivity patterns for conditions where the target speech is spatially-separated from competing noise. Operationally, any directional processing setting will improve the signal-to-noise ratio (SNR) if the target speech is in a region of high sensitivity (typically the front) and the competing noise is in a null region (Dillon, 2012; Ricketts, 2001). Under such conditions where there is an improvement in the SNR, directional processing is likely to result in less overall signal modification because the processed signal will be less noisy and will better approximate the envelope modulation patterns of the reference signal in quiet (e.g., Neher, 2014). Moreover, unlike fast-acting WDRC, directional processing typically operates in a distortionless manner, thereby preserving the envelope information in the target speech, and thus reducing the overall amount of signal modification. However, speech recognition benefit with directional processing depends on several factors. For instance, in optimal test conditions (e.g., laboratory settings, single noise source simulations, correlated noise sources), the improvement in SNR due to directional processing may be up to 7 dB (Ricketts, 2001; Bentler, 2005) versus ~2–3 dB in real-world environments (Compton-Conley et al., 2004). Other variables such as input SNRs (Walden et al., 2005), directional microphone configurations (Best et al., 2015; Picou et al., 2014), other environmental conditions such as reverberation or dynamic sound sources (e.g., Best et al., 2015; Ricketts & Hornsby, 2003, Wu et al., 2013), and individual audiograms (Gnewikow et al., 2009; Neher et al., 2017; Ricketts et al., 2005) also affect benefit from directional processing.

WDRC and Directionality

The combined effects of directionality and WDRC may be critical for good speech recognition for the following reasons. Across studies it has been shown that for input SNRs above 0 dB, the compressor responds to the most modulated signal, be it speech or noise, and may amplify the noise in the temporal gaps of speech (Naylor & Johannsen, 2009; Alexander & Masterson, 2015). This negative effect of compression is exacerbated at faster WDRC speeds (Alexander & Masterson, 2015; Souza et al., 2006). Because signal modification with WDRC depends on the input SNR to the compressor, and directional processing changes the SNR at the front-end of the hearing aid, the directionality setting in turn is likely to have an impact on the WDRC-processed signal.

Some early studies reported that the presence of WDRC (regardless of the compression speed) did not have an effect on benefits with directional processing (improvement in SNR relative to the omnidirectional setting) as long as the speech and competing noise from different angles arrived simultaneously at the microphones (Novick et al., 2001; Ricketts, 2000; Ricketts et al., 2001). This is expected because directional processing precedes WDRC in a hearing aid and gain is determined by the overall level of the signal entering through the microphones (Kates, 2008). That is, level estimation used by the compressor works on the combination of microphone signals used to create directionality. However, no evidence regarding the impact of directional processing on signal modification with WDRC is available from these studies.

On the other hand, Wu and Stangl (2013) presented speech and noise separated by 180 degrees for input SNRs ranging from −5 to +20 dB and showed that while SNR at the output decreased (and acceptable noise levels worsened) with WDRC relative to linear amplification, opposite effects were observed when directional processing was activated. It should be noted that for the WDRC condition, the study combined directional processing with digital noise reduction, making it difficult to parse the effect of directional processing alone on WDRC. Rhebergen et al. (2009) measured speech recognition in normal hearing listeners by applying fast-acting WDRC to the clean speech signal, before mixing with noise. Results showed that WDRC improved the audibility of weaker consonants and resulted in better speech recognition when a compression ratio of 2:1 was applied. Similarly, other studies have shown that improved audibility of speech in quiet has been associated with improved speech recognition with fast-acting WDRC, compared to linear amplification (Souza & Turner, 1998; 1999) or slow-acting WDRC (Kowalewski et al., 2018). More generally, there is evidence suggesting that distortion from fast-acting WDRC may be reduced if some form of processing is applied to effectively decouple the target speech from the background noise (May et al., 2018; Kowalewski et al., 2020) or reverberation (Hassager et al., 2017a; 2017b) prior to compression. Thus, the pattern of effects reported by Wu and Stangl combined with studies showing the improved audibility or reduced distortion with fast-acting WDRC on speech in quiet suggest that hearing aid directionality settings may impact outcomes with WDRC-related signal modification. It is likely that when directional processing separates the noise from the target speech before compression and results in a higher SNR (i.e., decreased background noise and improved speech audibility), the negative effect of WDRC (i.e., unfavorable signal modification with fast-acting WDRC) will be further reduced.

Working memory

In recent years, speech recognition outcomes related to the level of signal modification with WDRC have been shown to vary based on individual cognitive abilities, including working memory (the ability to simultaneously store and process information; Baddeley, 2000; Daneman & Carpenter, 1980). Studies have shown that hearing-impaired listeners with poorer working memory ability score lower than those with better working memory ability on speech recognition tasks using fast-acting WDRC (Lunner & Sundewall-Thorén, 2007; Ohlenforst et al., 2015; Souza et al., 2015). This association has been explained by the Ease of Language Understanding (ELU; Rönnberg et al., 2008; 2013) model – listeners with poorer working memory ability are negatively affected by fast-acting WDRC despite improvements in audibility, because fast WDRC modifies the speech envelope and causes a deviation from the original phonological representation (e.g., disruption of place of articulation cues, reduced consonant-vowel contrasts; Ellison et al., 2003; Jenstad & Souza, 2005). The listener has to draw from limited working memory resources to overcome the modifications and successfully identify the processed speech signal. In fact, the detrimental effect of fast-acting WDRC for listeners with poorer working memory ability has been shown to be greater at higher background noise levels (Lunner & Sundewall-Thorén, 2007) and with greater degrees of hearing loss (Souza et al., 2015).

There is some evidence that familiarization or experience with hearing aid signal processing may affect the strength of association between working memory ability and speech recognition. Rudner et al. (2011) studied a group of 30 experienced hearing aid users under conditions of “high degradation” (low SNR, modulated noise, and fast-acting WDRC) and “low degradation” (high SNR, steady noise, and slow-acting WDRC). Listeners were familiarized with fast- and slow-acting compression for 9 weeks each. The study found that the group of listeners with better working memory benefitted more from fast-acting WDRC in modulated noise than listeners with poorer working memory after the 9-week familiarization period. The authors suggested that listeners with poorer working memory may benefit more from slow-acting WDRC prior to a familiarization period. Recent studies have also observed that the role of working memory ability in aided speech recognition is reduced for experienced hearing aid users (Rählmann et al., 2018; Ng & Rönnberg, 2019) and is diminished after at least 6-months of experience for new hearing aid users (Ng et al., 2014). These observations are consistent with the ELU model in that experience with hearing aid signal processing is likely to minimize the mismatch between phonological representations in the brain and the incoming processed signal, thereby reducing the recruitment of working memory for speech recognition.

Nevertheless, evidence for the association of speech recognition with signal modification and working memory ability is limited in two ways. First, while previous studies using simulated hearing aid processing (Souza et al., 2015; Ohlenforst et al., 2015) and wearable devices (Gatehouse et al., 2003; 2006; Lunner & Sundewall-Thorén, 2007; Rudner et al., 2009; Souza & Sirow, 2014) demonstrated that as listening conditions become more challenging, the association between working memory ability and speech recognition becomes stronger, these studies provide evidence only for conditions where the hearing aid microphone is equally sensitive in all directions (i.e., omnidirectional settings). As such, these studies did not factor in additional changes in signal modification that may occur if directional processing precedes WDRC. As argued above, directional processing improves the SNR and has the potential to successfully counter the unfavorable signal modification with WDRC (especially fast-acting WDRC). Consequently, listeners with poorer working memory ability may benefit from conditions with less signal modification, brought about by directional processing (due to less background noise) even when combined with fast-acting WDRC, to reconcile the phonological mismatch in these conditions. Therefore, the likelihood that directional processing, when combined with WDRC, can reduce the dependence of speech recognition on working memory ability needs investigation.

Second, previous studies only varied relative speech and noise levels in collocated listening environments, to simulate SNR changes with directional processing. In doing so, the studies did not account for variation in the effectiveness of directional processing itself across several factors noted earlier (e.g., environmental SNRs, audiograms). Moreover, simulated SNR changes do not take into account other potential benefits with directional processing in spatially-separated speech and noise conditions, such as the opportunity to focus attention on a particular location or binaural advantages like the binaural masking level difference (Hirsh, 1948; Licklider, 1948; Zekveld et al., 2014). In other words, we need to account for the possibility that directional processing when operating in spatial listening conditions may modulate the relationship between speech recognition with WDRC processing and working memory ability, in a manner that is different from SNR variation in collocated conditions.

Purpose of the study

The present study was designed to evaluate how the relationship between speech recognition and working memory ability is mediated by signal modification with WDRC (fast-acting vs. slow-acting) and directionality (omnidirectional vs. fixed-directional) in wearable hearing aids. To capture the effects of directional processing, the study was conducted in spatially-separated speech and competing noise conditions, across a range of realistic SNRs. Based on evidence that overall signal modification is a strong predictor of speech recognition (Arehart et al., 2013; Souza et al., 2015; Souza et al., 2019), the combined effects of hearing aid processing conditions and SNRs were initially quantified using an envelope modification metric (cepstral correlation; Kates & Arehart, 2014). Next, the interaction between the resulting cumulative signal modification and individual working memory ability and their relative impact on speech recognition was analyzed. It was hypothesized that for hearing aid processing conditions that result in lower signal modification when combined (i.e., fixed-directional processing and slow-acting WDRC), there would be a weaker association between working memory ability and speech recognition.

MATERIALS & METHODS

Participants

Twenty-three individuals (15 males and 8 females) in the age range 59 to 92 years (M = 75.48, SD = 8.60) with bilateral mild- to moderately-severe sensorineural hearing loss participated in the study. Fourteen participants were existing hearing aid users. Pure-tone audiometric thresholds were obtained at octave and mid-octave frequencies between 250 Hz and 8000 Hz. None of the participants had asymmetry between the ears (asymmetry was defined as a difference of at least 15 dB HL at two or more frequencies or a difference of at least 20 dB HL at one frequency between 250 Hz and 3000 Hz). Difference in word recognition scores (NU-6; Tillman & Carhart, 1966) in quiet between the two ears was within 16% for all individuals. Air-bone gap was less than or equal to 10 dB at all test frequencies in each ear. Figure 1 shows the air conduction thresholds for the right and left ears of all participants. Mean four-frequency pure-tone average (PTA; 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) in the right ear was 40.98 dB HL (SD = 9.29) and in the left ear was 41.09 dB HL (SD = 10.02). A paired t test showed that the PTA for the right and left ears were not significantly different from each other (t=-0.12, p=0.91). PTA averaged for both ears was significantly correlated with age (r=0.435, p=0.038). All participants were native English speakers, reported no significant history of otologic or neurologic disorders, and were in general good health based on self-report. All participants had normal cognitive functioning based on the Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005; >= 23; Luis et al., 2009; Rossetti et al., 2011). All participants completed an informed consent process approved by the Institutional Review Board at Northwestern University.

Stimuli

Stimuli were Institute of Electrical and Electronics Engineers (IEEE) sentences (Rothauser et al., 1969) randomly sampled from a total set of 18 male and 15 female talkers from the University of Washington/ Northwestern University corpus (Panfili et al., 2017). The corpus consists of talkers from the Northern Cities and Pacific Northwest in the United States with a range of representative intelligibility across the regions[1] (McCloy et al., 2014). The choice of stimuli is based on evidence that the ability to recognize low-context spoken sentences (such as the IEEE sentences) presented in noise is related to working memory ability (e.g., Arehart et al., 2013; Souza et al., 2015; 2019). Multiple target talkers from both genders were included to improve the ecological validity of the study. Each IEEE sentence consisted of 5 keywords. Sentences were presented at four SNRs – 0 dB, 5 dB, 10 dB, and quiet. These SNRs were selected to represent the range of real-world SNRs (Smeds et al., 2015; Wu et al., 2018). Background noise consisted of four-talker babble from the Connected Speech Test (Cox et al., 1987).

Test room set up

The test room set up is shown in Figure 2. Participants were seated in the middle of a large (4.9 m x 4.3 m x 2.7 m) sound-attenuated room with 37 loudspeakers. Six loudspeakers and

---

[1] McCloy et al. (2014) reported that there was no significant effect of talker-dialect (Northern Cities vs. Pacific Northwest) on speech intelligibility for listeners from either region.

one subwoofer were located on each wall, with nine loudspeakers located in the ceiling of the room. The ambient reverberation time (T_{60}) of the room was approximately 0.2 s. Participants faced the front of the room and were allowed to freely move their head. The target speech was presented in front of the participant at 0 degrees azimuth. The babble sources were located at ±90 degrees (participants' left and right) and 180 degrees (behind the participant). A different, randomly-selected sample of 4-talker babble was presented from each loudspeaker, effectively resulting in 12-talker babble in terms of signal modulation. Because none of the loudspeakers in the room were directly at ear level, amplitude panning (Pulkki, 1997; Seldess, 2014) was used to simulate virtual sources at the desired azimuth at approximately ear level. Recent data suggest that this method for producing virtual sound sources is appropriate for older participants with hearing impairment without any additional filtering to achieve a particular frequency response at the ear (Ellis & Souza, 2020).

Speech was always presented at 65 dBA measured at approximately the center of the participant's head. The total level from all babble sources was varied between 65 and 55 dBA (depending on the desired SNR) by scaling the babble digitally before being played through the loudspeaker array. In the quiet listening condition, no babble was played. Babble was presented for 5 seconds before and 1 second after the target speech to ensure that hearing aid directionality was activated before the target speech was presented. Electroacoustic analysis (Audioscan Verifit 2) verified that full activation of directional processing would occur within that timeframe.

Hearing aid signal processing

A pair of commercially-available premium behind-the-ear (BTE) hearing aids from one manufacturer were used. This particular manufacturer was selected, in part, because the clinically available fitting software allowed the experimenter control over the WDRC speed. Two WDRC speed settings were used in this experiment: fast-acting WDRC (FAST) had an attack time of 12 ms and a release time of 70 ms, whereas slow-acting WDRC (SLOW) had an attack time of 30 ms and a release time of 4000 ms. The hearing aid applied multichannel WDRC using frequency warping over 17 channels (Groth & Nelson, 2005). Two hearing aid directionality settings were chosen: omnidirectional (OMNI) and fixed-directional (DIR). According to manufacturer specifications, the fixed-directional setting has a hypercardioid directional response pattern, which results in reduced sensitivity for sounds from the sides and rear. Fixed-directional processing was activated to include the lowest possible frequencies in the manufacturer's software (between 250 Hz and 500 Hz). Below these frequencies the hearing aid was omnidirectional even in the fixed-directional setting. Hearing aid processing conditions were programmed in four different memories (1=OMNI/FAST, 2=DIR/FAST, 3=OMNI/SLOW, 4=DIR/SLOW).

Bilateral hearing aids were coupled using full-shell custom acrylic earmolds with a 2-mm vent and standard #13 tubing. There were exceptions for six participants. One participant with a moderate flat hearing loss was fitted without a vent due to the severity of their loss. In addition, five participants were fitted with foam ear tips (no vent) due to unavailability of their custom molds at the time of testing. A paired *t* test showed no significant difference in performance due to coupling method (*p*=0.566). Therefore, data from all participants were combined in the analyses. Individualized frequency shaping was provided to all participants using the validated NAL-NL2 prescriptive method (Keidser et al., 2012). Low-frequency gain was automatically applied in the manufacturer's software in the fixed-directional setting to compensate for the low-frequency roll-off due to directional processing. The hearing aid was adjusted so that real-ear aided response (REAR) at 65 dB SPL input level would match NAL-NL2 targets (within +/− 5 dB between 250-3000 Hz) for the OMNI/SLOW program. For documentation/verification purposes, REARs were captured for the remaining three programs, but no adjustments were made or necessary. Figure 3 shows the average target match for all four programs across participants. The real-ear saturation response was measured at 85 dB SPL input level to ensure that the hearing aid output did not exceed predicted loudness discomfort levels. All other forms of advanced signal processing except automatic feedback suppression were turned off in all programs. Manual volume control was deactivated.

Working Memory

Working memory ability was measured using the Reading Span Test (RST; Rönnberg et al., 1989). The RST is a widely used test of verbal working memory that has been shown to have a robust association with speech recognition in noise (e.g., Souza & Arehart, 2015) across a range of hearing aid signal processing, including WDRC (e.g., Foo et al., 2007; Rudner et al., 2011; Souza & Sirow, 2014; Souza et al., 2015; 2019). Participants were presented with sentences one at a time in sets of three to six and instructed to make a judgment about the meaningfulness of each sentence. They were then instructed to recall either the first or last words (randomly selected) of each sentence in the set. The percentage of words recalled correctly (RST %) was used as the measure of the participant's working memory ability. The RST captures an individual's ability to coordinate simultaneous processing (assessment of meaningfulness of the sentence) and storage (recall of first or last words). The administration of RST is in the visual-verbal modality, thus ensuring that the accuracy of results will not be confounded by the loss of audibility for hearing-impaired listeners. RST scores ranged from 22.2 % to 57.4 % (M = 39.11 %) similar to the reported range in previous studies (e.g., Ohlenforst et al., 2015; Souza & Sirow, 2014; Souza et al., 2015). Pearson's Correlation Coefficients showed that RST % was significantly correlated with PTA (r=-0.543, p=<0.01), but not with age (r=-0.304, p=0.16), in our participant cohort. That is, individuals with a poorer RST also had more hearing loss.

Procedure

The study was completed in two visits. Participants completed pure tone audiometry, MOCA, RST, and earmold impressions in the first visit. Hearing aid fitting and speech recognition measures were completed in the second visit. Each visit lasted between 90–120 minutes. Speech recognition was measured for each participant in 16 conditions, including 4 SNRs x 4 hearing aid processing conditions (2 WDRC speeds X 2 directionality settings). Ten sentences (or 50 keywords) per condition were presented, resulting in a total of 160 sentences. The experiment was blocked by hearing aid program, and the order of presentation of the four hearing aid programming conditions was randomized across participants using a Latin-Square design. Within a program, the order of presentation of

SNRs was randomized for each participant. Each sentence was randomly drawn from the available set of talkers, and no sentence was repeated. The participant was seated in the center of the room and instructed to repeat the sentences they heard from the front (Figure 2). The presentation of programs was controlled through an iPad connected to the hearing aids via Bluetooth. The participant was blinded to the hearing aid signal processing conditions. Stimuli were presented using custom MATLAB software (Mathworks, Inc., Natick, MA), and routed through an M-Audio Quad audio interface. Participants repeated the sentence and received one point for every keyword they repeated correctly. No feedback was given.

Hearing aid Recordings

Monaural hearing aid recordings were obtained for the exact signal processing conditions presented to the participants following methods specified in Kates et al. (2018) and Rallapalli et al. (2019). To obtain these recordings, the right hearing aid was programmed for a participant and mounted on an acoustic manikin (Knowles Electronics Manikin for Acoustics Research, KEMAR) placed in the center of the experimental room. The signal was routed from KEMAR through the M-Audio Quad digital-to-audio converter and recorded into MATLAB. The hearing aid was coupled to KEMAR's right pinna with a full-shell custom earmold (2-mm vent) or a foam tip (for the five exceptions noted above). The stimuli for the recordings consisted of a repeated IEEE sentence ("It is late morning on the old wall clock") spoken by one male then by one female talker from the same database, presented at 65 dBA. The sentences were mixed with 4-talker babble at four different SNRs as described in 'Room set up'. Ten iterations of the stimulus were recorded and averaged to obtain the final recording at each SNR for a given hearing aid program (i.e., WDRC-directionality combination). In addition to averaging, the signals were high-pass filtered at 80 Hz to remove interfering noise (Kates et al, 2018). Following the above procedure, an unaided recording was also obtained in quiet to serve as a reference signal.

Signal Modification

Signal modification was measured using the cepstral correlation component associated with the Hearing aid Speech Quality Index (HASQI; Kates & Arehart, 2014). Cepstral correlation compares the envelope modulation in the hearing aid output at a given time and frequency to that of a reference signal. The reference condition was obtained from the unaided recording in quiet and processed with NAL-R. Both the hearing aid processed and reference signals were passed through a model of the individual's damaged auditory periphery that accounts for the frequency-specific threshold shift and associated broadened auditory filters (Kates, 2013). Specifically, the model consists of an auditory filterbank (32-channel gammatone filterbank with center frequencies between 80–8000 Hz), followed by dynamic-range compression of the outer hair cells, firing-rate adaptation of the neural response, and the auditory threshold. Spectral ripple values from ½ to 2 ½ cycles per spectrum are obtained by fitting short-term auditory spectra (in dB) with a set of spectral smoothing functions. These ripple values are correlated over time for the reference and processed signals and averaged to obtain the cepstral correlation term. Cepstral correlation values range from 0 (poorest reproduction of temporal envelope) to 1 (perfect reproduction of temporal envelope). Specific details on the calculation procedures are available in Kates & Arehart (2014). For easier interpretation, final signal modification values are converted to 1 minus cepstral correlation, such that 0 represents least signal modification and 1 represents maximum signal modification.

RESULTS

Signal Modification

The study focused on the relationship between working memory ability and speech recognition across levels of signal modification (combination of hearing aid processing and the listening environment). Therefore, the first step was to consider the effect of our experimental conditions on signal modification (cepstral correlation), using a linear mixed-effects (LME) model in SAS 9.4. Separate LME models were computed at each SNR. This approach was chosen because the signal processing in the hearing aid at a given SNR would have acted independent of other SNRs, and previous research has shown that SNRs used in this study should have a large and significant effect on signal modification (e.g., Souza et al., 2015; 2019). Indeed, the large effect of SNR is evident in Figure 4, where the greatest signal modification (higher values) was measured at 0 dB SNR and the least signal modification was measured in quiet. Fixed factors in each model included directionality setting (OMNI and DIR), WDRC speed (FAST and SLOW), and their two-way interaction. PTA (right) was also included in the model to determine whether signal modification would be related to the degree of hearing loss. PTA was centered by subtracting the mean before entering it in the model. The Benjamini and Hochberg (1995) false discovery rate correction (FDR) was applied to account for multiple comparisons. Residual diagnostics confirmed model assumptions.

LME model results at each SNR are shown in Table 1. At 0 dB and 5 dB SNRs, only the main effects of directionality and WDRC were significant such that the signal modification was greater for OMNI relative to DIR, and for FAST relative to SLOW (Figure 4). At 10 dB SNR, the interaction between WDRC and directionality was significant. Paired t tests within each directionality setting showed that FAST resulted in greater signal modification than SLOW in the OMNI condition (t= 3.17, p=<0.001), but there was no significant difference in signal modification between FAST and SLOW in the DIR condition (t=-0.03, p=0.975). In quiet, none of the signal processing conditions had a significant effect on signal modification (p>0.05), as expected. These results illustrate a complex relationship between WDRC and directionality’s effects on signal modification that varies with SNR. PTA (right) was significant at each SNR, such that signal modification decreased slightly at greater degrees of hearing loss when noise was present. This is consistent with the nature of the signal modification metric which discards portions of the signal that are below threshold (Kates et al., 2018).

Speech Recognition

A per-talker analysis for speech recognition in quiet revealed that average performance with three of the randomly sampled talkers (1 male and 2 females) was substantially low (< 80% correct) across participants. Based on this analysis, data from these 3 talkers were excluded, resulting in dropping 1–4 sentences for certain conditions for a subset of participants (n =

13). Final speech recognition scores were the percentage of keywords repeated correctly, adjusted for total number of keywords presented per condition. A one-way analysis of variance revealed no significant difference in speech recognition between the group of 13 participants with reduced keywords and the remaining group of 10 participants ($F[1,367]=0.000$, $p=0.977$). A separate one-way ANOVA revealed no significant difference in RST% between the two groups of participants ($F[1,21]=0.165$, $p=0.688$). Figure 5 shows the final distribution of percent correct scores across the four SNRs and each hearing aid processing condition.

To determine whether the relationship between speech recognition (percent correct scores) and working memory ability depended on the level of signal modification (i.e., the combined effects of background noise, PTA, and hearing aid signal processing, including directionality and WDRC), another LME model was implemented in SAS 9.4. Considering that there was no effect of hearing aid signal processing (i.e., directionality or WDRC) on signal modification in quiet (Table 1 and Figure 4), only the percent correct scores for 0 dB, 5 dB, and 10 dB SNRs were included in the analyses. The LME model consisted of fixed effects of signal modification (1 minus cepstral correlation), working memory ability (RST %), and the interaction between signal modification and working memory ability. Both variables were continuous and were centered at the mean. Initially, hearing aid experience was entered as a between-subjects variable in the model, but there was no main effect or significant interactions of hearing aid experience with other variables ($p > 0.05$). As it was not a primary factor of interest in this study, we excluded hearing aid experience from the final model. Model fit was determined using the Akaike Information Criterion (Akaike, 1974). Residual diagnostics were carried out to verify model assumptions (the Shapiro-Wilk test confirmed that residuals were normally distributed; $p>0.05$). None of the variables needed transformation.

The LME model results for speech recognition are shown in Table 2. The main effects of signal modification and RST% on percent correct scores were significant. The two-way interaction between signal modification and RST % was also significant, indicating that the effect of RST% (working memory ability) on percent correct scores depended on the level of signal modification. This interaction is depicted in Figure 6, which shows the predicted percent correct scores from the LME model as a function of RST %. For a meaningful interpretation of the interaction between two continuous measures (signal modification and RST%), four values of signal modification were selected (Table 3). These values are the average signal modification measured for each hearing aid processing condition, averaged across SNRs and participants. The lines in Figure 6 show the relationship between percent correct scores and RST% at each value of signal modification, representing a hearing aid processing condition. Notice that the lines representing OMNI are at a greater observed signal modification level than DIR. Within each directionality condition, the lines representing FAST are at a greater observed signal modification level than SLOW.

Post-hoc analyses were conducted to determine the strength of association of percent correct scores with RST% at each of the four selected levels of signal modification. Simple slopes computed at each level of signal modification reveal the following: when signal modification is at OMNI/FAST ($b=0.0062$, 95% CI [-0.001, 0.013], $t=1.7$, $p=0.09$) or OMNI/SLOW (*b*=0.0067, 95% CI [-0.0005, 0.014], *t*=1.84, *p*=0.067), there is no significant relationship between RST% and percent correct scores. However, when signal modification is at DIR/FAST (*b*=0.0085, 95% CI [0.001, 0.016], t=2.33, *p*=0.02) and DIR/SLOW (*b*=0.0087, 95% CI [0.001, 0.016], *t*=2.38, *p*=0.018), there is a significant positive relationship between RST% and percent correct scores. To generalize the interpretation of the two-way interaction, two additional levels of signal modification were assessed. Simple slopes computed at 1 SD above (0.614) overall mean observed signal modification revealed no significant relationship between RST% and percent correct scores (*b*=0.0049, 95% CI [-0.002, 0.012], *t*=1.33, *p*=0.184), whereas the simple slope computed at 1 SD below the mean observed signal modification (0.325) revealed a significant positive relationship between RST% and percent correct scores (*b*=0.01, 95% CI [0.003, 0.017], *t*=2.70, *p*=0.007).

Together, the results indicate that the relationship between RST% and percent correct scores is mediated by the level of observed signal modification. Moreover, higher coefficient estimates indicate a stronger association between RST% and percent correct scores at lower levels of observed signal modification. This relationship is further illustrated in the following example: a change in RST% from 22.2% (individual with the poorest RST score) to 57.4% (individual with the best RST score) resulted in an increase in predicted speech recognition by 21.93% when signal modification was held constant at 0.544 (OMNI/FAST; experimental condition with the greatest observed signal modification), versus an increase in predicted speech recognition by 30.59% when signal modification was held constant at 0.405 (DIR/SLOW; experimental condition with the lowest observed signal modification).

DISCUSSION

The goal of the present study was to evaluate how the relationship between speech recognition and working memory ability is mediated by cumulative signal modification with WDRC (fast-acting vs. slow-acting) and directionality (omnidirectional vs. fixed-directional). This relationship was studied in spatially-separated speech and noise conditions, using wearable hearing aids.

Signal Modification

First, cumulative signal modification across experimental conditions including hearing aid processing and different background noise levels was analyzed. When noise was present, the fixed-directional setting always resulted in lower signal modification over the omnidirectional setting, consistent with an improvement in SNR (Arehart et al., 2013; Neher, 2014; Rallapalli et al., 2019; Souza et al., 2015; 2019) and speech audibility. This is consistent with the behavior of the hypercardiod directional response pattern used in this study which was most sensitive to the target speech from the front and reduced the competing noise from the sides and the rear to improve the SNR (Bentler et al., 2004; Ricketts, 2001; Wu & Stangl, 2013). Such evidence of improvement in SNR with directional processing after combining with WDRC is in accordance with previous studies where significant directional benefits were reported even in the presence of WDRC or digital noise reduction (Neher, 2014; Novick et al., 2001; Ricketts, 2000; Ricketts et al., 2001; Wu & Stangl, 2013).

As hypothesized, the directionality setting had an impact on signal modification with WDRC, and this effect was modulated by the SNR. At lower SNRs (0 dB and 5 dB), regardless of the directionality setting, the signal modification due to fast-acting WDRC was always greater than slow-acting WDRC. On the other hand, at a higher SNR (10 dB), the signal modification due to WDRC depended on the directionality setting, such that fast-acting WDRC resulted in greater modification of the signal over slow-acting WDRC only in the omnidirectional setting. The direction of effects with WDRC-related signal modification is similar to previous reports (Kates et al., 2018; Souza et al., 2015; 2019) and can be attributed to greater temporal envelope degradations caused by fast-acting WDRC (Ellison et al., 2003; Jenstad & Souza, 2005; Stone & Moore, 2007; 2008) compared to slow-acting WDRC. Unlike the omnidirectional setting, however, in the fixed-directional processing setting at 10 dB SNR, there was no difference in signal modification between fast-acting and slow-acting WDRC.

There may be two underlying mechanisms at play here, one related to the action of the compressor and the other related to the signal modification metric (cepstral correlation). For sentences mixed with noise, the compressor responds to the more modulated signal, which tends to be the speech signal at positive SNRs. For such signals, it has been shown that WDRC reduces the long-term SNR at the output (Naylor and Johanneson, 2009; Rhebergen et al., 2017) and that this effect is more pronounced at faster WDRC speeds (Alexander & Masterson, 2015; Souza et al., 2006). The reference signal in the calculation of cepstral correlation was a linearly amplified signal without noise. Consequently, deviations from the speech envelope (reference signal) were more pronounced for fast-acting WDRC, resulting in greater signal modification (smaller cepstral correlation value) compared to slow-acting WDRC at a given input SNR. This may explain the effects observed at 0 dB and 5 dB SNRs and in the omnidirectional setting at 10 dB SNR. Next, with the activation of fixed-directional processing, especially at 10 dB SNR, the overall noise levels were reduced to inaudible levels, making the envelope characteristics of the signal after WDRC comparable to the linearly amplified reference signal, regardless of the WDRC speed. Therefore, there was no effect of WDRC speed on signal modification in this condition. A similar effect is also evident in quiet, where hearing aid processing did not result in any significant modification of the signal relative to the reference (Kates et al., 2018).

The above findings illustrate the importance of quantifying the cumulative effects of hearing aid signal processing across a range of background noise levels. These results also indicate that directional processing may have a positive impact on subsequent signal processing in a hearing aid, such as WDRC, and that directional processing can successfully counter the modification arising from fast-acting WDRC depending on the SNR in the listening environment. Similar to the present study, Neher (2014) reported lower signal modification at SNRs of -4, 0, and +4 dB with a cardiod directional processing setting, as well as an added advantage of reduced speech degradation for digital noise reduction schemes when preceded by directional processing.

Speech Recognition

Consistent with previous research, the effect of working memory ability on speech recognition depended on the level of cumulative signal modification. For example, Souza et al. (2015) and Souza et al. (2019) showed that when two hearing aid signal processing mechanisms such as WDRC and frequency lowering were combined to result in different levels of signal modification, working memory ability played a significant role in speech recognition. In the present study, it was hypothesized that the association of working memory ability with speech recognition will become weaker at lower levels of signal modification (resulting from fixed-directional processing, slow-acting WDRC and reduced background noise). In support of this hypothesis, Neher (2014) reported a small effect of working memory in predicting digital noise reduction outcomes (speech recognition and subjective preference) in the omnidirectional condition but no effect of working memory in the directional processing condition. Similarly, Souza et al. (2015) reported that as the level of signal modification decreased at higher SNRs, the differences in speech recognition performance between better and poorer working memory groups decreased.

However, results from the present study were contrary to the above hypothesis such that the association between working memory ability and speech recognition was in fact significant at lower levels of signal modification (i.e., levels representing fixed-directional processing and higher SNRs) and was not significant at greater levels of signal modification (i.e., levels representing omnidirectional processing and lower SNRs). That is, all participants regardless of their working memory had poor speech recognition at greater levels of signal modification (unfavorable conditions), whereas speech recognition in noise increased as a function of working memory ability at lower levels of signal modification (favorable conditions). Furthermore, as the level of signal modification decreased, speech recognition increased at a higher rate as a function of working memory ability. That is, listeners with better working memory ability benefitted more with the decrease in signal modification, compared to listeners with poorer working memory ability. A recent study has shown a similar pattern of results with wearable hearing aids. Souza et al. (2019) conducted a double-blind crossover clinical trial with 40 hearing-impaired adults who were fitted with either mild (slow-acting WDRC without frequency compression) or strong (fast-acting WDRC and nonlinear frequency compression) signal modification. All listeners performed poorly with strong signal modification, regardless of their working memory ability, but listeners with better working memory benefitted more with mild signal modification compared to those with poorer working memory.

The pattern of results in the present study may be partly explained by the tradeoff between audibility and distortion with hearing aid processing. Studies have shown that hearing aid processing such as fast-acting WDRC is beneficial for speech recognition up to the point where enough speech cues become audible (Davies-Venn et al., 2009; Souza & Turner, 1998). But once audibility plateaus, the speech that is being made more audible is no longer useful and the processing may result in degrading speech recognition because important cues such as the temporal envelope can be distorted. Put differently, in this study, because equal audibility was achieved by an adequate match-to-prescriptive targets (Figure 3) with both WDRC speeds in the omnidirectional programs, fast-acting WDRC may not have been advantageous over slow-acting WDRC for any listener. Consequently, at greater levels of signal modification, such as omnidirectional processing with fast- or slow-acting WDRC, all listeners had poor speech recognition, regardless of their working memory ability. The finding that individuals with better working memory ability derived greater speech recognition benefit from decreasing the level of signal modification (favorable conditions including fixed-directional settings and improved SNRs) than individuals with poorer working memory ability, is not fully understood. It is speculated that at lower levels of signal modification, listeners with better working memory were able to segregate the preserved speech cues from noise more effectively than individuals with poorer working memory ability (Gatehouse et al., 2003; 2006) or that individuals with poorer working memory ability were limited in their ability to segregate speech cues under the conditions tested, despite improvements in SNR and less signal distortion at lower levels of signal modification. Further research is needed to explain the pattern of results obtained in the present study and in the study of Souza et al. (2019).

Regarding other relevant work in this area, Neher et al. (2018) compared performance across various forms of noise suppression, including cardioid directional processing, two types of digital noise reduction, and no processing. They reported that while cardioid directional processing resulted in the best speech recognition overall, there was no association of working memory ability with outcomes across these conditions. The authors speculated that their measures of working memory ability may not have been sensitive to modifications from the specific hearing aid processing conditions. Keidser et al. (2013) also reported that cognitive abilities including working memory, selective attention, and processing speed did not contribute to variability in directional benefits for a large group of hearing-impaired adults. Their study used high predictability sentences that may be less sensitive to differences in working memory ability than the IEEE sentences used in this study (Cox & Xu, 2010). Moreover, in contrast with the present study, directionality was not combined with any other hearing aid signal processing in either of these studies. These factors may have contributed to the different findings between previous work and the work presented here.

There were also several methodological differences from previous studies that evaluated the relationship between WDRC, signal modification, and working memory ability. One is the use of spatially-separated speech and noise in this study versus collocated speech and noise in previous studies. We argue that the use of spatially-separated speech and noise is a more realistic representation of listening conditions (e.g., Wu et al., 2018), and is necessary to document the effects of directionality. The finding that RST % was a significant factor in this study suggests that working memory continues to play a significant role in speech recognition in spatially-separated speech and noise conditions for hearing-impaired listeners. That said, future studies should continue to explore the relationship between working memory and speech recognition in the context of hearing aid signal processing and realistic listening environments.

A second methodological difference between the work presented here and previous work is the inclusion of multiple male and female talkers in the speech recognition task. Previous studies have frequently used a single female talker (e.g., Lunner & Sundewall-Thorén, 2007;

Ohlenforst et al., 2015; Souza et al., 2015). While the decision to include several talkers in the present study was motivated by ecological validity, there may be complex interactions of talker and gender, especially when listening in certain spatial conditions (e.g., Best et al., 2013; Freyman et al., 2001; Zekveld et al., 2014). An investigation of talker effects is outside the scope of this study, but it is possible that an interplay of factors including talker gender, number, and spatial configuration may have contributed to the pattern of results and needs to be addressed in future work.

Future work could also examine the effects of reverberation on these results. Reverberation is an important factor in real world listening environments and has been shown to affect the relationship between signal modification and working memory (Reinhart and Souza, 2016; Reinhart et al., 2019). These studies showed that reverberation reduces the strength of the relationship between working memory and signal modification such that the effects of working memory disappear at reverberation times greater than or equal to 1.5s. As this work moves toward more realistic listening environments, reverberation will be an important factor to consider.

There are some listener-related considerations as well. In the participant cohort here, working memory ability was significantly correlated with PTA such that individuals with poorer RST scores also had greater degrees of hearing loss. Therefore, PTA and RST % could not be entered in the same statistical model. However, this potential confound was addressed in two ways. The main concern with PTA is related to the extent of the signal that is above threshold. In this study, all participants received an excellent match to NAL-NL2 targets (Figure 3). In addition, the cepstral correlation metric accounted for individual hearing loss and its effects on envelope modification (Kates & Arehart, 2014; Kates et al., 2018).

It is noteworthy that over half the listeners in this study were experienced hearing aid users. Therefore, the possibility that hearing aid experience may have played a role in speech recognition outcomes (e.g., Ng & Rönnberg, 2019) was explored. Two-sample t tests showed that there was no significant difference in RST% (t=1.68, p=0.11) between experienced and non-hearing aid users. Further, there was no significant effect of hearing aid experience on speech recognition scores (F[1,345]=2.41, p=0.121). Some recent studies have also put forth the argument that acclimatization to hearing aid signal processing over 6 months is likely to reduce the contribution of working memory in speech recognition (e.g., Ng et al., 2014). Therefore, it is possible that participants in this study may have acclimatized to directionality and WDRC conditions and shown a weaker association with working memory, had they been given extended time with the hearing aids. It is also worth noting that speech recognition with hearing aid signal processing including WDRC and directionality has been associated with cognitive factors other than working memory, such as listening effort (Desjardin, 2016; Picou et al., 2014; Picou & Ricketts, 2017) and executive function (Neher et al., 2016). The relative contributions of these cognitive factors in understanding hearing aid processed speech needs further research.

This study focused on only one fixed-directional (hypercardioid) processing pattern that was suitable for the frontal target and diffuse noise source conditions presented here. However modern hearing aids provide other directional processing patterns (e.g., beamformers, adaptive, asymmetric) that may result in different amounts of benefit depending on the alignment of the null region with the competing noise or the ability of the hearing aid user to orient to the target signal (e.g., Best et al., 2015). Consequently, the combination of directional processing patterns and spatial conditions may result in different levels of signal modification, which in turn may interact differently with individual working memory ability to impact speech recognition. These factors should therefore be studied systematically in future work.

Finally, regarding measurements using KEMAR, previous work has shown that cepstral correlation measured on hearing aid output from KEMAR can effectively capture vent effects and ear canal acoustics (Rallapalli et al., 2019). That said, KEMAR is representative of the *average* human ear, and does not precisely represent each individual human ear. It is possible that measuring signal modification with KEMAR's earmold may have under- or over- estimated ear acoustics (and consequently the signal modification) for some participants in this study. Our lab is actively investigating methods to capture signal modification from human ears (Rallapalli, in press). These methods will be applied to future research to better account for individual ear acoustics for relating hearing aid signal modification to behavioral outcomes.

CONCLUSIONS

This study demonstrates that working memory ability remains a significant predictor of speech recognition when signal modification is determined by a combination of WDRC and hearing aid directionality. This was demonstrated under clinically-relevant conditions, including spatially-separated speech and multi-talker babble, with clinically-realistic hearing aids and signal processing settings. Findings from this study revealed that directional processing can reduce the detrimental acoustic effects of fast-acting WDRC at higher SNRs and is an important factor in determining hearing aid signal modification and subsequent speech recognition ability. While the effects of directional processing are to improve the SNR and decrease signal modification, relying on SNR-alone as a proxy for these effects may not present the entire picture. Contrary to some previous research, this study showed that individuals with better working memory ability benefitted more from a decrease in signal modification than individuals with poorer working memory ability. There may have been several methodological differences contributing to this discrepancy that need to be addressed systematically in future research.

From a clinical standpoint, the findings advocate for the use of directional processing for all hearing aid users in challenging listening conditions. This is especially important in the context of reports indicating that hearing aid users utilize this function only a small percentage of the time (e.g., Banerjee, 2011). While individuals with better working memory benefitted more with less signal modification through the use of fixed-directional processing and slow-acting WDRC, the findings lead us to speculate whether individuals with poorer working memory may be limited in their ability to utilize speech cues even at lower levels of signal modification (i.e., favorable conditions). Alternatively, individuals with poorer working memory may require much lower levels of signal modification to perform on par with individuals with better working memory. Future studies must address other clinically relevant situations by investigating alternative directional processing patterns and other realistic spatial conditions.

ACKNOWLEDGMENTS

This work was supported by the National Institutes of Health Grant R01 DC012289 (to P.S.) and K01 DC018324 (to V.R.). Portions of these data were presented at the 46th Annual and Scientific Technology Conference of the American Auditory Society, Scottsdale, Arizona, March, 2019.

Financial Disclosures/Conflicts of Interest:

This research was funded by National Institutes of Health.

REFERENCES

Akaike H (1974). A new look at the statistical model identification. IEEE Trans Automat Contr, 19, 716–723.

Alexander JM, & Masterson K (2015). Effects of WDRC release time and number of channels on output SNR and speech recognition. Ear Hear, 36(2), e35–49. doi:10.1097/aud.0000000000000115 [PubMed: 25470368]

Arehart KH, Souza P, Baca R, et al. (2013). Working memory, age, and hearing loss: susceptibility to hearing aid distortion. Ear Hear, 34(3), 251–260. doi:10.1097/AUD.0b013e318271aa5e [PubMed: 23291963]

Arehart K, Souza P, Kates J, Lunner T, & Pedersen MS (2015). Relationship between signal fidelity, hearing loss and working memory for digital noise suppression. Ear Hear, 36(5), 505. [PubMed: 25985016]

Baddeley A (2000). The episodic buffer: a new component of working memory? Trends Cogn Sci, 4(11), 417–423. [PubMed: 11058819]

Banerjee S (2011). Hearing Aids in the Real World: Typical Automatic Behavior of Expansion, Directionality, and Noise Management. J Am Acad Audiol, 22, 34–48. 10.3766/jaaa.22.1.5 [PubMed: 21419068]

Benjamini Y, & Hochberg Y (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. J R Stat Soc Series B (Methodological), 57(1), 289–300.

Bentler R (2005). Effectiveness of directional microphones and noise reduction schemes in hearing aids: a systematic review of the evidence. J Am Acad Audiol, 16(7), 473–484. [PubMed: 16295234]

Bentler RA, Egge JL, Tubbs JL, et al. (2004). Quantification of directional benefit across different polar response patterns. J Am Acad Audiol, 15(9), 649–659; quiz 660. doi:10.3766/jaaa.15.9.6 [PubMed: 15575339]

Best V, Thompson ER, Mason CR, et al. (2013). An energetic limit on spatial release from masking. J Assoc Res Otolaryngol, 14(4), 603–610. doi:10.1007/s10162-013-0392-1 [PubMed: 23649712]

Best V, Mejia J, Freeston K, et al. (2015). An evaluation of the performance of two binaural beamformers in complex and dynamic multitalker environments. Int J Audiol, 54(10), 727–735. doi: 10.3109/14992027.2015.1059502 [PubMed: 26140298]

Compton-Conley CL, Neuman AC, Killion MC, et al. (2004). Performance of directional microphones for hearing aids: real-world versus simulation. J Am Acad Audiol, 15(6), 440–455. doi:10.3766/jaaa.15.6.5 [PubMed: 15341225]

Cox RM, Alexander GC, & Gilmore C (1987). Development of the Connected Speech Test (CST). Ear Hear, 8(5 Suppl), 119S–126S. [PubMed: 3678650]

Cox RM, Xu J (2010). Short and long compression release times: speech understanding, real-world preferences, and association with cognitive ability. J Am Acad Audiol, 21 121–138. 10.3766/jaaa.21.2.6 [PubMed: 20166313]

Daneman M, & Carpenter PA (1980). Individual differences in working memory and reading. J Verbal Learn Verbal Behav, 19, 450–466. 10.1016/S0022-5371(80)90312-6.

Davies-Venn E, Souza P, Brennan M, et al. (2009). Effects of audibility and multichannel wide dynamic range compression on consonant recognition for listeners with severe hearing loss. Ear Hear, 30(5), 494–504. doi:10.1097/AUD.0b013e3181aec5bc [PubMed: 19633563]

Davies-Venn E, & Souza P (2014). The role of spectral resolution, working memory, and audibility in explaining variance in susceptibility to temporal envelope distortion. J Am Acad Audiol, 25(6), 592–604. [PubMed: 25313549]

Desjardins JL (2016). The Effects of Hearing Aid Directional Microphone and Noise Reduction Processing on Listening Effort in Older Adults with Hearing Loss. J Am Acad Audiol, 27(1), 29–41. [PubMed: 26809324]

Dillon H (2012). Hearing Aids (2 ed.). Sydney: Thieme.

Ellis GM, & Souza PE (2020). The effect of hearing loss on localization of amplitude-panned and physical sources. J Am Acad Audiol, 31(9).

Ellison J, Harris F, & Mueller HG (2003). Interactions of hearing aid compression release time and fitting formula: Effects on speech acoustics. J Am Acad Audiol, 14(2), 59–71. [PubMed: 12830842]

Foo C, Rudner M, Rönnberg J, et al. (2007). Recognition of speech in noise with new hearing instrument compression release settings requires explicit cognitive storage and processing capacity. J Am Acad Audiol, 18(7), 618–631. [PubMed: 18236648]

Freyman RL, Balakrishnan U, & Helfer KS (2001). Spatial release from informational masking in speech recognition. J Acoust Soc Am, 109(5), 2112–2122. [PubMed: 11386563]

Gatehouse S, Naylor G, & Elberling C (2003). Benefits from hearing aids in relation to the interaction between the user and the environment. Int J Audio,. 42, S77–S85. 10.3109/14992020309074648

Gatehouse S, Naylor G, & Elberling C (2006) Linear and nonlinear hearing aid fittings – 1. Patterns of benefit. Int J Audio, 45(3), 130–152, doi: 10.1080/14992020500429518

Gnewikow D, Ricketts T, Bratt GW, et al. (2009). Real-world benefit from directional microphone hearing aids. J Rehabil Res Dev, 46(5), 603–618. [PubMed: 19882494]

Groth J, & Nelson JA (2005). Human Resolution WarpTM [White paper]. Retrieved on 1–30-20, from https://cdn1-originals.webdamdb.com

Hassager HG, Wiinberg A, & Dau T (2017a). Effects of hearing-aid dynamic range compression on spatial perception in a reverberant environment. J Acoust Soc Am, 141(4), 2556–2568. [PubMed: 28464692]

Hassager HG, May T, Wiinberg A, & Dau T (2017b). Preserving spatial perception in rooms using direct-sound driven dynamic range compression. J Acoust Soc Am, 141(6), 4556–4566. [PubMed: 28679250]

Henning RL, & Bentler RA (2008). The effects of hearing aid compression parameters on the short-term dynamic range of continuous speech. J Speech Lang Hear Res, 51(2), 471–484. doi:10.1044/1092-4388(2008/034) [PubMed: 18367690]

Hirsh IJ (1948). The influence of interaural phase on interaural summation and inhibition. J Acoust Soc Am, 20(4), 536–544.

Jenstad LM, & Souza P (2005). Quantifying the effect of compression hearing aid release time on speech acoustics and intelligibility. J Speech Lang Hear Res, 48(3), 651–667. doi:10.1044/1092-4388(2005/045) [PubMed: 16197279]

Kates JM (2008). Digital Hearing Aids. San Diego, CA: Plural Publishing.

Kates JM (2013). An auditory model for intelligibility and quality predictions. Proc. Mtgs. Acoust. (POMA) 19, 050184: Acoust. Soc. Am. 165th Meeting, Montreal, 6 2–7, 2013.

Kates JM, & Arehart KH (2014). The hearing aid speech quality index (HASQI) version 2. J Audio Eng Soc, 62(3), 99–117.

Kates JM, Arehart KH, Anderson MC, et al. (2018). Using Objective Metrics to Measure Hearing Aid Performance. Ear Hear, 39(6), 1165–1175. doi:10.1097/aud.0000000000000574 [PubMed: 29554034]

Keidser G, Dillon H, Carter L, et al. (2012). NAL-NL2 empirical adjustments. Trends Amplif, 16(4), 211–223. [PubMed: 23203416]

Keidser G, Dillon H, Convery E, et al. (2013). Factors influencing individual variation in perceptual directional microphone benefit. J Am Acad Audiol, 24, 955–968. [PubMed: 24384081]

Kim G, & Loizou PC (2011). Gain-induced speech distortions and the absence of intelligibility benefit with existing noise-reduction algorithms. J Acoust Soc Am, 130(3), 1581–1596. doi:10.1121/1.3619790 [PubMed: 21895096]

Kowalewski B, Zaar J, Fereczkowski M, et al. (2018). Effects of Slow- and Fast-Acting Compression on Hearing-Impaired Listeners' Consonant-Vowel Identification in Interrupted Noise. Trends Hear, 22, 1–12. doi:10.1177/2331216518800870

Kowalewski B, Dau T, & May T (2020). Perceptual Evaluation of Signal-to-Noise-Ratio-Aware Dynamic Range Compression in Hearing Aids. Trends Hear, 24. doi:10.1177/2331216520930531

Licklider JCR (1948). The influence of interaural phase relations upon the masking of speech by white noise. J Acoust Soc Am, 20(2), 150–159.

Luis CA, Keegan AP, & Mullan M (2009). Cross validation of the Montreal Cognitive Assessment in community dwelling older adults residing in the Southeastern US. Int J Geriatr Psychiatry, 24(2), 197–201. [PubMed: 18850670]

Lunner T, & Sundewall-Thorén E (2007). Interactions between cognition, compression, and listening conditions: Effects on speech-in-noise performance in a two-channel hearing aid. J Am Acad Audiol, 18(7), 604–617. [PubMed: 18236647]

May T, Kowalewski B, & Dau T (2018). Signal-to-Noise-Ratio-Aware Dynamic Range Compression in Hearing Aids. Trends Hear, 22, doi: 10.1177/2331216518790903.

McCloy DR, Wright RA, & Souza P (2014). Talker versus dialect effects on speech intelligibility: A symmetrical study. Lang Speech, 58(0 3), 371–386.

McDermott HJ (2011). A technical comparison of digital frequency-lowering algorithms available in two current hearing aids. PLoS One, 6(7), e22358. [PubMed: 21789254]

Nasreddine ZS, Phillips NA, Bédirian V, et al. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J Am Geriatr Soc, 53(4), 695–699. [PubMed: 15817019]

Naylor G, & Johannesson RB (2009). Long-term signal-to-noise ratio at the input and output of amplitude-compression systems. J Am Acad Audiol, 20(3), 161–171. [PubMed: 19927686]

Neher T (2014). Relating hearing loss and executive functions to hearing aid users' preference for, and speech recognition with, different combinations of binaural noise reduction and microphone directionality. Front Neurosci, 8, 391. [PubMed: 25538547]

Neher T, Wagener KC, & Latzel M (2017). Speech reception with different bilateral directional processing schemes: Influence of binaural hearing, audiometric asymmetry, and acoustic scenario. Hear Res, 353, 36–48. doi:10.1016/j.heares.2017.07.014 [PubMed: 28783570]

Neher T, Wagener KC, & Fischer R-L. (2018) Hearing aid noise suppression and working memory function, Int J Audiol, 57:5, 335–344, doi: 10.1080/14992027.2017.1423118 [PubMed: 29316819]

Ng EH, Classon E, Larsby B, et al. (2014). Dynamic relation between working memory capacity and speech recognition in noise during the first 6 months of hearing aid use. Trends Hear, 18, 1–10.

Ng EH, & Rönnberg J (2019) Hearing aid experience and background noise affect the robust relationship between working memory and speech recognition in noise. Int J Audiol, 10.1080/14992027.2019.1677951

Novick ML, Bentler RA, Dittberner A, et al. (2001). Effects of release time and directionality on unilateral and bilateral hearing aid fittings in complex sound fields. J Am Acad Audiol, 12(10), 534–544. [PubMed: 11791940]

Ohlenforst B, Souza P, & Macdonald EN (2015). Exploring the relationship between working memory, compressor speed and background noise characteristics. Ear Hear, 37, 137–143.

Panfili LM, Haywood J, McCloy DR, et al. (2017). The UW/NU Corpus, Version 2.0. https://depts.washington.edu/phonlab/projects/uwnu.php

Picou EM, Aspell E, & Ricketts TA (2014). Potential benefits and limitations of three types of directional processing in hearing aids. Ear Hear, 35(3), 339–352. doi:10.1097/aud.0000000000000004 [PubMed: 24518429]

Picou EM, & Ricketts TA (2017) How directional microphones affect speech recognition, listening effort and localisation for listeners with moderate-to-severe hearing loss, Int J Audiol, 56(12), 909–918. [PubMed: 28738747]

Pulkki V (1997). Virtual sound source position using vector base amplitude panning. J Audio Eng So, 45(6), 456–466.

Rählmann S, Meis M, Schulte M, Kießling J, Walger M, & Meister H (2018). Assessment of hearing aid algorithms using a master hearing aid: the influence of hearing aid experience on the relationship between speech recognition and cognitive capacity. Int J Audiol, 57(sup3), S105–S111.

Rallapalli VH, Mueller A, Appleton R, et al. (2018). Survey of hearing aid signal processing features across manufacturers. Paper presented at the American Academy of Audiology 2018, Nashville, TN.

Rallapalli V, Anderson M, Kates J, et al. (2019). Quantifying the Range of Signal Modification in Clinically Fit Hearing Aids. Ear Hear, 41(2), 433–441. doi:10.1097/aud.0000000000000767

Rallapalli V (in press). Can Hearing Aid Signal Fidelity be Measured Under Clinical Conditions? Hear J.

Reinhart PN & Souza PE (2016). Intelligibility and clarity of reverberant speech: Effects of wide dynamic range compression release time and working memory. J Speech Lang Hear Res, 59(6), 1543–1554. [PubMed: 27997667]

Reinhart PN, Zahorik P, & Souza PE (2019). Effects of Reverberation on the Relation Between Compression Speed and Working Memory for Speech-in-Noise Perception. Ear Hear, 40(5), 1098–1105. [PubMed: 31025984]

Rhebergen KS, Versfeld NJ, & Dreschler WA (2009). The dynamic range of speech, compression, and its effect on the speech reception threshold in stationary and interrupted noise. J Acoust Soc Am, 126(6), 3236–3245. [PubMed: 20000937]

Rhebergen KS, Maalderink TH, & Dreschler WA (2017). Characterizing Speech Intelligibility in Noise After Wide Dynamic Range Compression. Ear Hear, 38(2), 194–204. doi:10.1097/aud.0000000000000369 [PubMed: 27749521]

Ricketts T (2000). Directivity quantification in hearing aids: fitting and measurement effects. Ear Hear, 21(1), 45–58. [PubMed: 10708073]

Ricketts T (2001). Directional Hearing Aids. Trends Amplif, 5(4), 139–176. doi:10.1177/108471380100500401 [PubMed: 25425906]

Ricketts T & Hornsby B (2003). Distance and Reverberation Effects on Directional Benefit. Ear Hear, 24(6), 472–84. doi:10.1097/01.AUD.0000100202.00312.02. [PubMed: 14663347]

Ricketts TA, Henry PP, & Hornsby BW (2005). Application of frequency importance functions to directivity for prediction of benefit in uniform fields. Ear Hear, 26(5), 473–486. doi:10.1097/01.aud.0000179691.21547.01 [PubMed: 16230897]

Ricketts T, Lindley G, & Henry P (2001). Impact of compression and hearing aid style on directional hearing aid benefit and performance. Ear Hear, 22(4), 348–361. [PubMed: 11527041]

Rönnberg J, Arlinger S, Lyxell B, et al. (1989). Visual evoked potentials: Relation to adult speechreading and cognitive function. J Speech Hear Res, 32, 725–735. [PubMed: 2601304]

Rönnberg J, Rudner M, Foo C, et al. (2008). Cognition counts: a working memory system for ease of language understanding (ELU). Int J Audiol, 47(Suppl 2), S99–105. doi:10.1080/14992020802301167 [PubMed: 19012117]

Rönnberg J, Lunner T, Zekveld A, et al. (2013). The Ease of Language Understanding (ELU) model: theoretical, empirical, and clinical advances. Front Syst Neurosci, 7(31). doi:10.3389/fnsys.2013.00031

Rossetti HC, Lacritz LH, Cullum CM, et al. (2011). Normative data for the Montreal Cognitive Assessment (MoCA) in a population-based sample. Neurology, 77(13), 1272–1275. [PubMed: 21917776]

Rothauser EH, Chapman WD, Guttman N, et al. (1969). IEEE recommended practice for speech quality measurements. IEEE Trans Acoust, 17, 225–246.

Rudner M, Foo C, Rönnberg J, & Lunner T (2009). Cognition and aided speech recognition in noise: specific role for cognitive factors following nine-week experience with adjusted compression settings in hearing aids. Scand J Psychol, 50, 405–418. doi: 10.1111/j.1467-9450.2009.00745.x [PubMed: 19778388]

Rudner M, Rönnberg J, & Lunner T (2011). Working memory supports listening in noise for persons with hearing impairment. J Am Acad Audiol, 22(3), 156–167. [PubMed: 21545768]

Seldess Z (2014). MIAP: manifold-interface amplitude panning in Max/MSP and pure data. Paper presented at the Audio Engineering Society Convention 137.

Smeds K, Wolters F, & Rung M (2015). Estimation of signal-to-noise ratios in realistic sound scenarios. J Am Acad Audiol, 26(2), 183–196. [PubMed: 25690777]

Souza P, & Arehart KH (2015). Robust relationship between reading span and speech recognition in noise. Int J Audiol, 54(10), 705–713. [PubMed: 25975360]

Souza P, Arehart KH, Shen J, et al. (2015). Working memory and intelligibility of hearing aid processed speech. Front Psychol, 6, 526. doi:10.3389/fpsyg.2015.00526 [PubMed: 25999874]

Souza P, Arehart K, Schoof T, et al. (2019). Understanding Variability in Individual Response to Hearing Aid Signal Processing in Wearable Hearing Aids. Ear Hear, 40(6), 1280–1292. doi:10.1097/aud.0000000000000717 [PubMed: 30998547]

Souza P, Jenstad LM, & Boike KT (2006). Measuring the acoustic effects of compression amplification on speech in noise. J Acoust Soc Am, 119(1), 41–44. [PubMed: 16454262]

Souza P, & Sirow L (2014). Relating working memory to compression parameters in clinically fit hearing aids. Am J Audiol, 23(4), 394–401. [PubMed: 25123548]

Souza P, & Turner CW (1998). Multichannel compression, temporal cues, and audibility. J Speech Lang Hear Res, 41(2), 315–326. [PubMed: 9570585]

Souza P, & Turner CW (1999). Quantifying the contribution of audibility to recognition of compression-amplified speech. Ear Hear, 20(1), 12–20. doi:10.1097/00003446-199902000-00002 [PubMed: 10037062]

Stone MA, & Moore BC (2007). Quantifying the effects of fast-acting compression on the envelope of speech. J Acoust Soc Am, 121(3), 1654–1664. [PubMed: 17407902]

Stone MA, & Moore BCJ (2008). Effects of spectro-temporal modulation changes produced by multi-channel compression on intelligibility in a competing-speech task. J Acoust Soc Am, 123(2), 1063–1076. doi:10.1121/1.2821969 [PubMed: 18247908]

Tillman TW, & Carhart R (1966). An expanded test for speech discrimination utilizing CNC monosyllabic words: Northwestern University Auditory Test No. 6. USAF School of Aerospace Medicine, Brooks Air Force Base, TX.

Walden BE, Surr RK, Grant KW, et al. (2005). Effect of signal-to-noise ratio on directional microphone benefit and preference. J Am Acad Audiol, 16(9), 662–676. [PubMed: 16515138]

Wu YH, & Stangl E (2013). The effect of hearing aid signal-processing schemes on acceptable noise levels: Perception and prediction. Ear Hear, 34(3), 333–341. [PubMed: 23334355]

Wu YH, Stangl E, Bentler RA, et al. (2013). The effect of hearing aid technologies on listening in an automobile. J Am Acad Audiol, 24(6), 474–485. doi:10.3766/jaaa.24.6.4 [PubMed: 23886425]

Wu YH, Stangl E, Chipara O, et al. (2018). Characteristics of Real-World Signal to Noise Ratios and Speech Listening Situations of Older Adults With Mild to Moderate Hearing Loss. Ear Hear, 39(2), 293–304. doi:10.1097/aud.0000000000000486 [PubMed: 29466265]

Zekveld AA, Rudner M, Kramer SE, et al. (2014). Cognitive processing load during listening is reduced more by decreasing voice similarity than by increasing spatial separation between target and masker speech. Front Neurosci, 8, 88. doi:10.3389/fnins.2014.00088 [PubMed: 24808818]

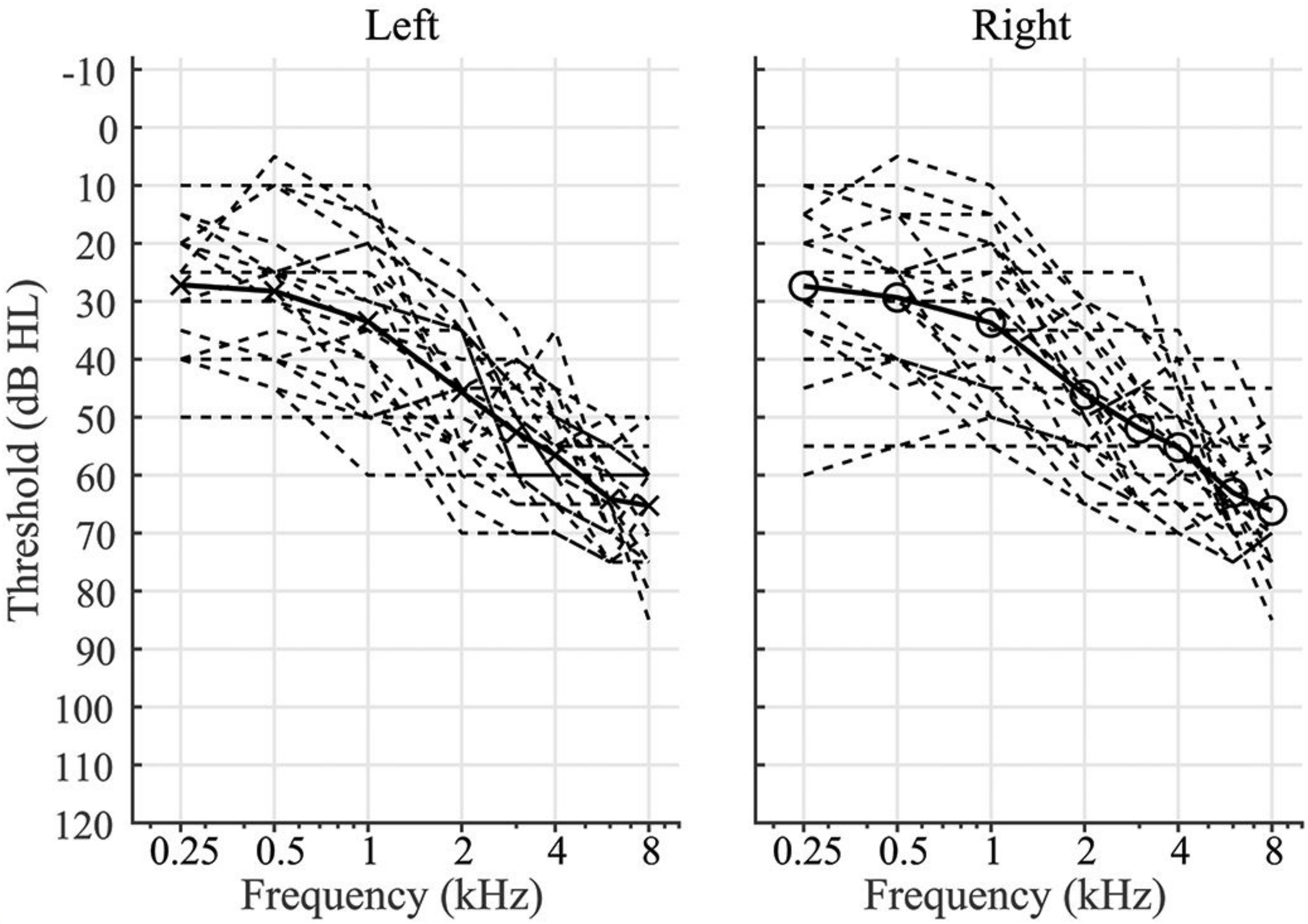

Figure 1.

Audiograms for left and right ears of each participant (dashed lines). Solid black line shows the average for all participants.

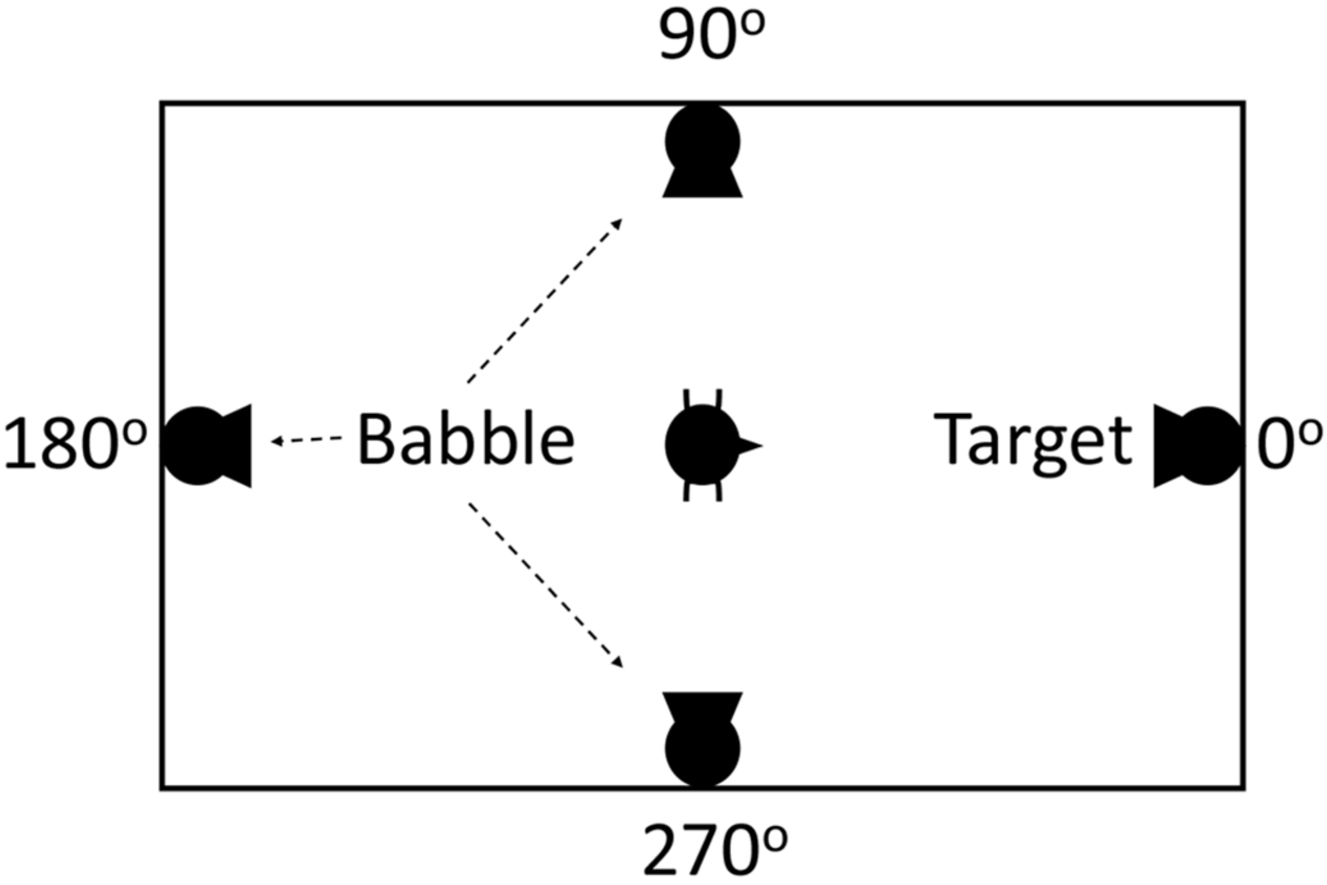

Figure 2.

Top-down view of the room set up (dimensions: 4.9m x 4.3m x 2.7m). The participant was seated in the center of the room. The target speech was presented from a virtual speaker in the front (0°) and babble was presented from three virtual speakers to the sides (90° & 270°) and the rear (180°) of the participant.

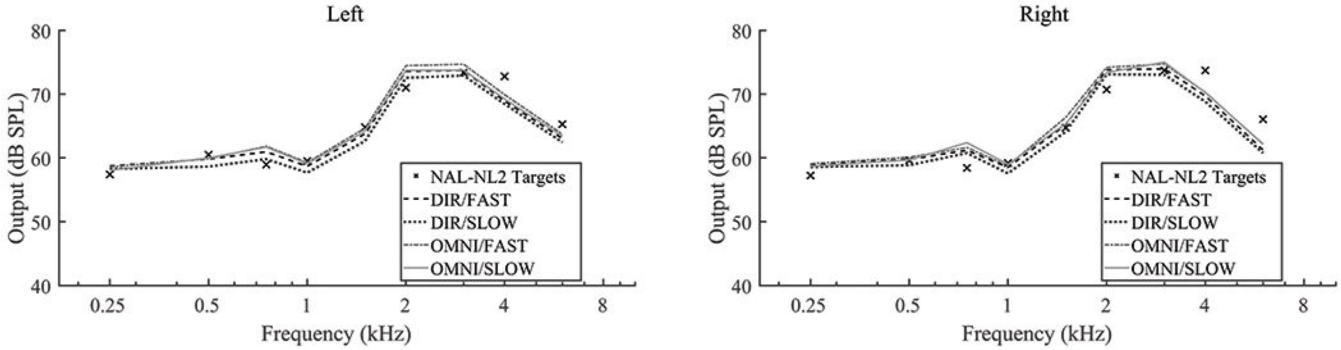

Figure 3.

Average NAL-NL2 prescribed targets (‘Xs’) and measured real-ear aided response (REAR) at 65 dB SPL for each hearing aid program (lines; see legend). Left and right ears are shown in separate panels.

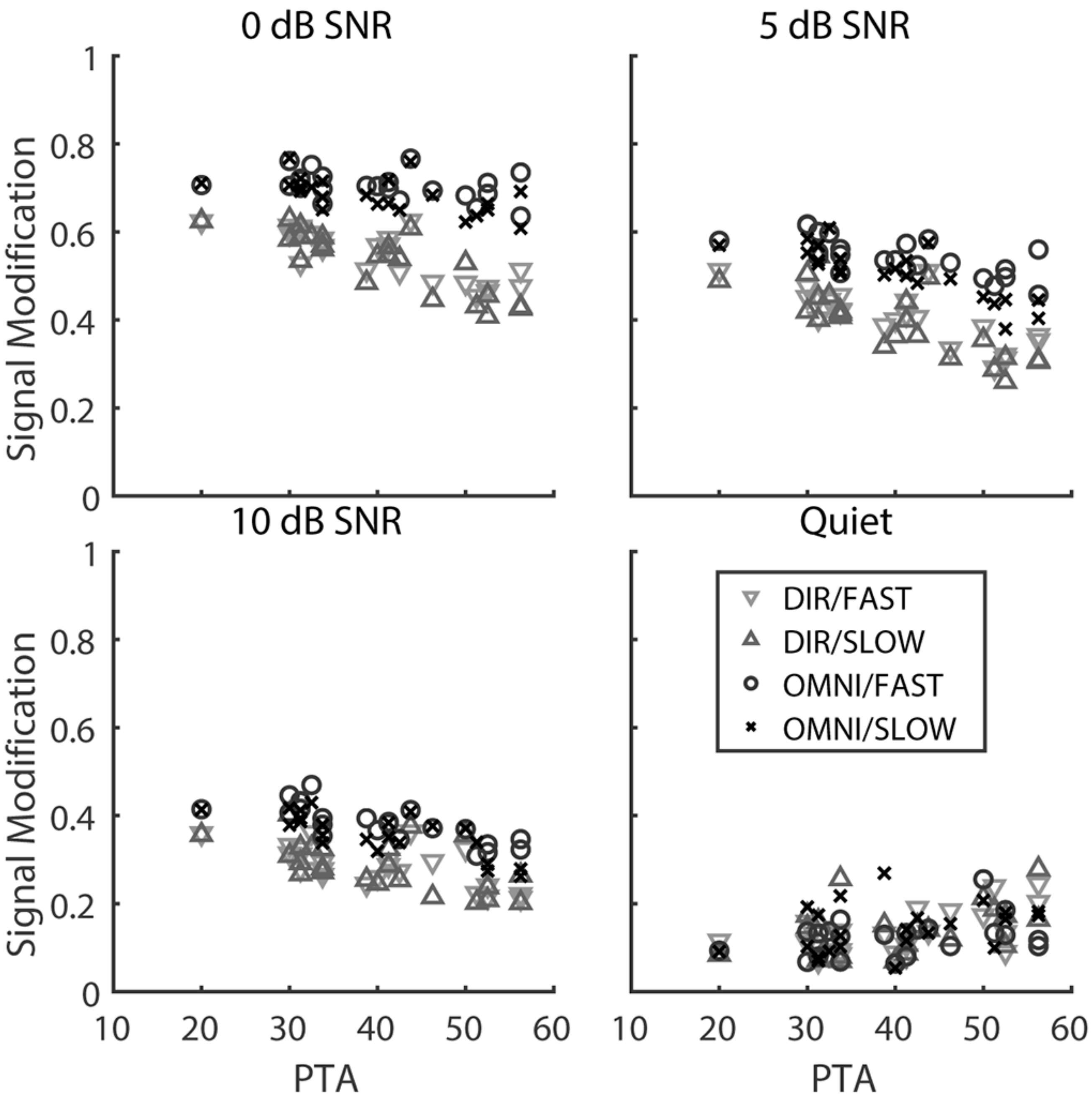

Figure 4.

Signal modification (cepstral correlation; 1 = maximum signal modification) measured for each hearing aid processing condition (legend) as a function of PTA (right ear). Each panel shows a different signal-to-noise ratio (SNR). Each data point represents one condition measured for an individual participant.

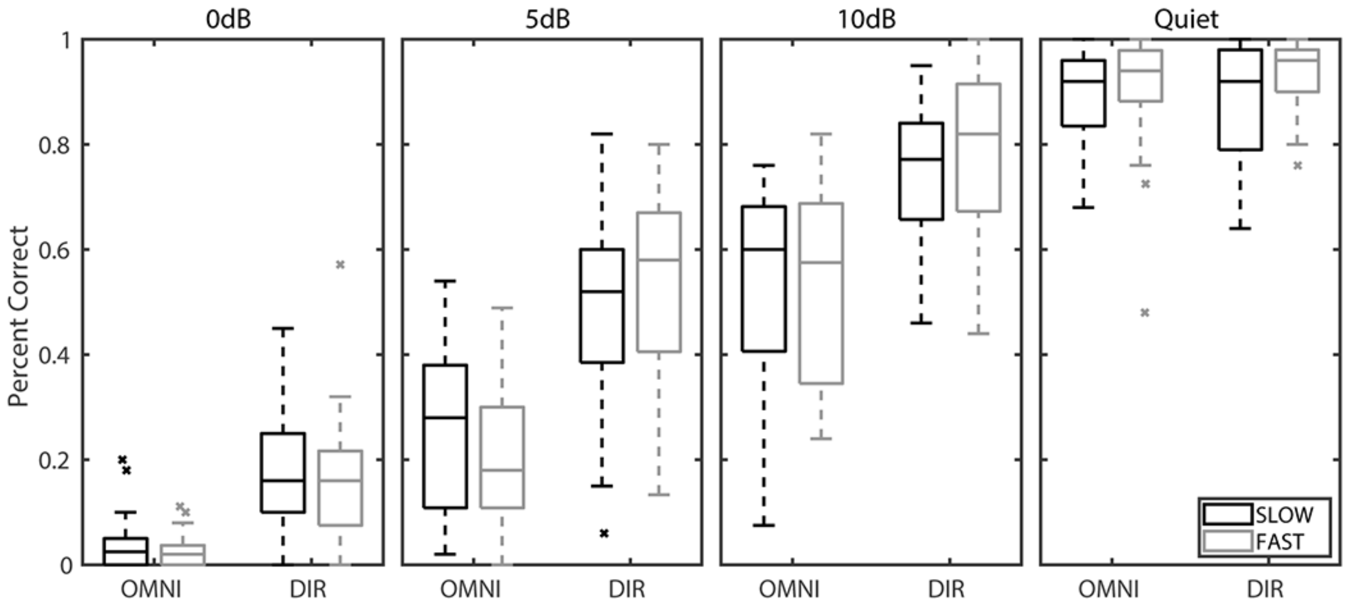

Figure 5.

Box plots showing the effect of hearing aid signal processing condition (directionality (*x*-axis) and WDRC (groups)) on speech recognition (percent correct; *y*-axis) for IEEE sentences. Each panel represents a different SNR. Center lines on each box represent the median. Box boundaries (dark boundaries for SLOW, light grey boundaries for FAST) represent the 25th and 75th percentiles. Data points that fell more than 1.5x the interquartile range were considered outliers and plotted as “x’s”. Whiskers extend to the last data point not considered to be an outlier.

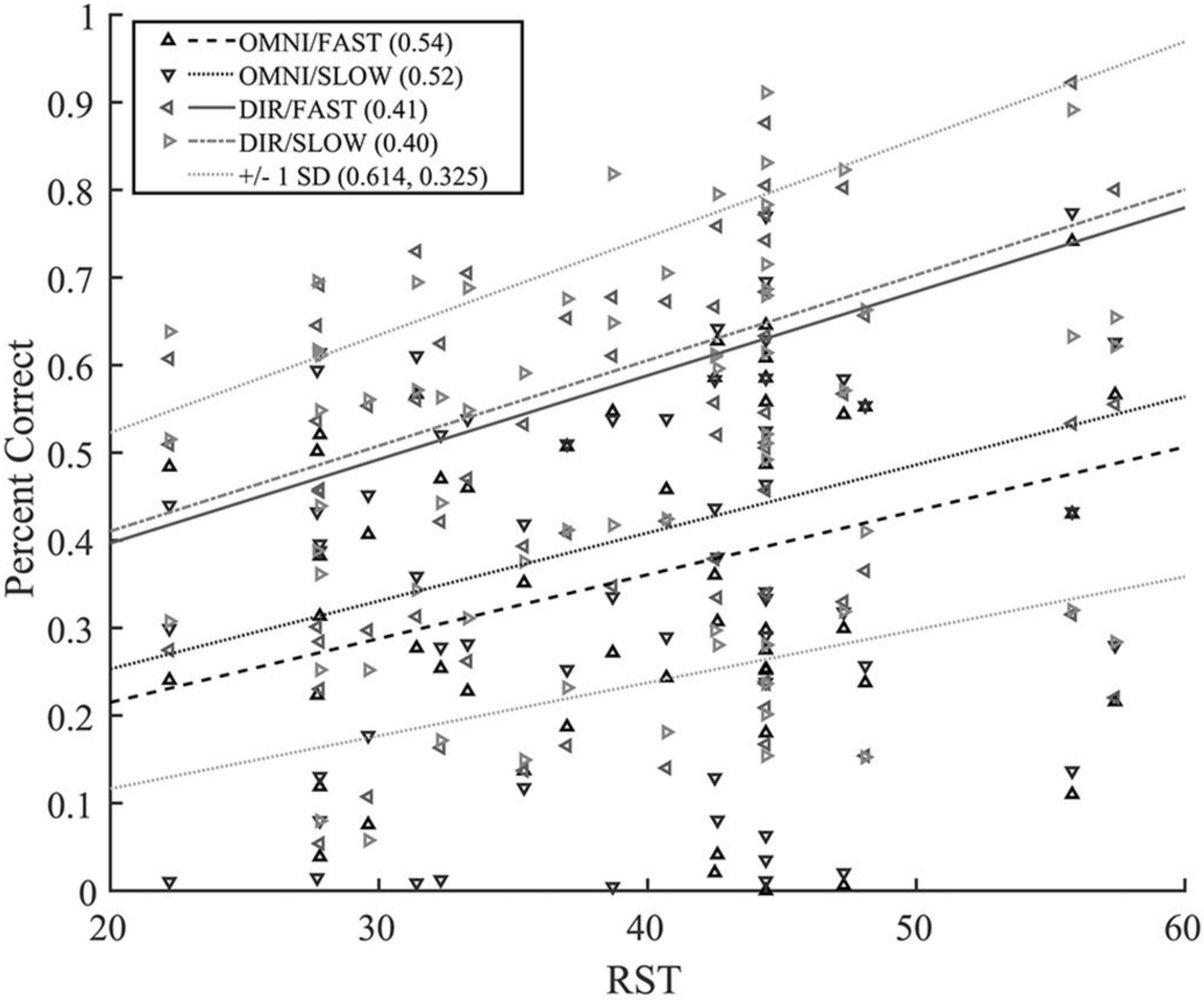

Figure 6.

Relationships between working memory ability (RST%; *x*-axis) and speech recognition (percent correct; *y*-axis) at different signal modification levels (lines). Predictions for the four lines in the middle were based on mean signal modification levels (1=maximum signal modification) for each hearing aid condition (averaged across participants and SNRs). Predictions for the top and bottom lines were based on signal modification levels ±1 SD around the overall mean signal modification level. See the parentheses in the legend or Table 3 for the specific signal modification values. Open triangles show the individual predicted percent correct scores by hearing aid processing condition (see legend) from the LME model.

Table 1.

LME model for the effect of hearing aid processing condition (ref = OMNI and SLOW) and PTA (Right; four-frequency pure tone average) on signal modification (cepstral correlation; 1 = maximum signal modification). Each signal-to-noise ratio (SNR) is a separate model.

		0 dB SNR		
Effect	***b***	***SE***	***p***	***b* 95% CI [LL, UL]**
Intercept	0.684	0.008	$<0.001^{***}$	[0.668, 0.701]
Directionality	−0.150	0.009	$<0.001^{***}$	[−0.168, −0.132]
WDRC	0.020	0.009	0.03^{*}	[0.002, 0.038]
Directionality*WDRC	−0.006	0.013	0.637	[−0.032, 0.020]
PTA (Right)	−0.004	0.001	$<0.001^{***}$	[−0.005, −0.003]
		5 dB SNR		
Intercept	0.508	0.008	$<0.001^{***}$	[0.490, 0.525]
Directionality	−0.114	0.008	$<0.001^{***}$	[−0.130, −0.097]
WDRC	0.037	0.008	$<0.001^{***}$	[0.020, 0.053]
Directionality*WDRC	−0.021	0.012	0.072	[−0.045, 0.002]
PTA (Right)	−0.005	0.001	$<0.001^{***}$	[−0.006, −0.003]
		10 dB SNR		
Intercept	0.358	0.008	$<0.001^{***}$	[0.343, 0.374]
Directionality	−0.072	0.007	$<0.001^{***}$	[−0.085, −0.059]
WDRC	0.024	0.007	$<0.001^{***}$	[0.011, 0.037]
Directionality*WDRC	−0.025	0.009	0.01^{*}	[−0.043, −0.006]
PTA (Right)	−0.004	0.001	$<0.001^{***}$	[−0.005, −0.002]
		Quiet		
Intercept	0.143	0.010	$<0.001^{***}$	[0.122, 0.165]
Directionality	−0.005	0.011	0.632	[−0.027, 0.016]
WDRC	−0.020	0.011	0.073	[−0.041, 0.002]
Directionality*WDRC	0.014	0.015	0.365	[−0.017, 0.045]
PTA (Right)	0.002	0.001	0.037^{*}	[0.0001, 0.004]

Estimates (*b*), standard error (SE), *p*-values (***p<0.001, **p<0.01, *p<0.05), and 95% confidence intervals of estimates (*b* 95% CI: LL=lower level, UL=upper level) are shown for fixed-effects in all models.

Table 2.

LME model for the effect of signal modification (cepstral correlation; 1 = maximum signal modification), and RST (Reading Span Test, %) on percent correct scores.

Effect	***b***	**SE**	***p***	***b* 95% CI [LL, UL]**
Intercept	0.379	0.033	$<0.001^{***}$	[0.311, 0.447]
Signal Modification	−1.744	0.053	$<0.001^{***}$	[−1.849, −1.639]
RST	0.0075	0.004	0.039^{*}	[0.0004, 0.015]
Signal Modification * RST	−0.018	0.006	0.003^{**}	[−0.029, −0.006]

Estimates (*b*), standard error (SE), *p*-values (***p<0.001, **p<0.01, *p<0.05), and 95% confidence intervals of estimates (*b* 95% CI: LL=lower level, UL=upper level) are shown for fixed-effects in the model.

Table 3.

Signal modification levels (cepstral correlation; 1 = maximum signal modification) measured for each hearing aid signal processing condition averaged across participants and SNRs. Standard deviations are reported in parentheses.

Condition	Signal modification
OMNI/FAST	0.544 (0.138)
OMNI/SLOW	0.517 (0.143)
DIR/FAST	0.415 (0.121)
DIR/SLOW	0.405 (0.123)