JSLHR

Research Article

Intelligibility and Clarity of Reverberant Speech: Effects of Wide Dynamic Range Compression Release Time and Working Memory

Paul N. Reinhart[a] and Pamela E. Souza[a,b]

Purpose: The purpose of this study was to examine the effects of varying wide dynamic range compression (WDRC) release time on intelligibility and clarity of reverberant speech. The study also considered the role of individual working memory.

Method: Thirty older listeners with mild to moderately-severe sloping sensorineural hearing loss participated. Individuals were divided into high and low working memory groups on the basis of the results of a reading span test. Participants listened binaurally to sentence stimuli simulated at a range of reverberation conditions and WDRC release times using a high compression ratio. Outcome measures included objective intelligibility and subjective clarity ratings.

Results: Speech intelligibility and clarity ratings both decreased as a function of reverberation. The low working memory group demonstrated a greater decrease in intelligibility with increasing amounts of reverberation than the high working memory group. Both groups, regardless of working memory, had higher speech intelligibility and clarity ratings with longer WDRC release times. WDRC release time had a larger effect on speech intelligibility under more reverberant conditions.

Conclusions: Reverberation significantly affects speech intelligibility, particularly for individuals with lower working memory. In addition, longer release times in hearing aids may improve listener speech intelligibility and clarity in reverberant environments.

Age-related, sensorineural hearing loss, or presbycusis, is characterized primarily by loss of hearing sensitivity. Presbycusis may be accompanied by processing deficits, which distort acoustic signals, such as broadened auditory filters (Festen & Plomp, 1983; Hopkins & Moore, 2011; Leek & Summers, 1993; Peters & Moore, 1992) and reduced temporal resolution (Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Hopkins & Moore, 2007; Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006; Nelson & Freyman, 1987). As a consequence, the neural representation of speech cues is likely to be degraded in individuals with hearing impairment even when the speech is fully audible (Tremblay, Piskosz, & Souza, 2003).

Associated with these auditory processing changes, individuals with hearing impairment are more susceptible to the distortive effects of reverberation than individuals with normal hearing even when the presentation level assures audibility (Duquesnoy & Plomp, 1980; Gordon-Salant & Fitzgibbons, 1993, 1995; Halling & Humes, 2000; Humes & Christopherson, 1991; Marrone, Mason, & Kidd, 2008). Reverberation is a common source of distortion present in nearly all listening environments. It is characterized by sound energy reflecting off of surfaces in an environment and arriving at the listener at a delay relative to the direct energy. Individuals with hearing impairment regard their ability to communicate in highly reverberant environments (e.g., places of worship, theaters, etc.) as important and may begin to avoid those environments if they have difficulty communicating (Gopinath et al., 2012; Reinhart & Souza, 2015).

For individuals with hearing impairment who seek to improve communication, hearing aids are the most widely distributed rehabilitation device. However, many hearing aid users continue to report dissatisfaction with their device's performance in challenging environments, including reverberation (Kochkin, 2010). Individuals who perceive their hearing aids as not effective across a range of environments are also more likely to discontinue use (Kochkin, 2000). Given these facts and the frequency with which listening occurs in reverberant spaces, there is a paucity of information

---

[a]Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL
[b]Knowles Hearing Center, Evanston, IL

Correspondence to Paul N. Reinhart: preinhart@u.northwestern.edu

Editor: Nancy Tye-Murray
Associate Editor: Todd Ricketts

Received October 28, 2015
Revision received January 24, 2016
Accepted May 23, 2016
DOI: 10.1044/2016_JSLHR-H-15-0371

Disclosure: The authors have declared that no competing interests existed at the time of publication.

regarding how to optimize hearing aids for reverberant environments.

Wide dynamic range compression (WDRC) is the core processing strategy in modern digital hearing aids. The purpose of WDRC is to balance an individual's need for gain with the limitations of a reduced dynamic range. This is achieved by applying different amounts of gain on the basis of the level of input, such that low-intensity inputs will receive more gain than high-intensity inputs. WDRC systems can be set to react to incoming sounds and adjust the gain at different speeds. WDRC release time is a key parameter of this system as it partially dictates at what rate gain is modulated in response to the sound input.

In clinical hearing aids, WDRC release times range widely from a few milliseconds to several seconds. In general, short release times provide improved audibility because the compressor rapidly increases gain to lower-intensity sounds. This quick gain restoration places more of the speech cues in an audible range for individuals with hearing impairment (Henning & Bentler, 2008; Jenstad & Souza, 2005; Souza, 2002). However, the rapid gain alterations that occur with short WDRC release times can also take a toll on the temporal characteristics of the signal. The amplitude differences among phonemes in the speech signal (i.e., the temporal envelope) contain important linguistic information regarding manner of articulation, voicing, and prosody (Rosen, 1992). As a result, shorter release times have also been shown to degrade speech recognition compared with longer release times, particularly for certain phonemes (Jenstad & Souza, 2005; Stone & Moore, 2004, 2007). Given the trade-offs between short and long WDRC release times, there is little agreement on how they should be set.

A recent study by Reinhart, Souza, Srinivasan, and Gallun (2016) investigated the effects of reverberation and WDRC release time on consonant recognition for nonsense syllables in individuals with hearing impairment. It was found that individuals had improved recognition with less reverberation as well as with longer WDRC release times. In addition, the authors applied an acoustic measure of envelope distortion to examine the combined effects of reverberation and WDRC release time on the acoustics. Nonsense syllable stimuli were analyzed using the envelope difference index (Fortune, Woodruff, & Preves, 1994) to quantify the effects of reverberation and WDRC release time on individual phonemes. This acoustic model has prevalent use in the hearing aid literature for examining the consequences of WDRC on nonsense syllables. Consistent with previous findings, the authors concluded that short WDRC release times distort the temporal envelope more than long release times even when the speech is first affected by reverberation. There were no interactions between reverberation and WDRC release time either behaviorally or acoustically.

The results of Reinhart et al. (2016) provide valuable insight into the relationship between reverberation and WDRC release time on a phonemic level. However, nonsense syllables presented without semantic or higher linguistic content also lack real-world validity. Information about longer speech segments with more real-life linguistic content is needed to direct choice of amplification processing in reverberant environments.

In a partial examination of such issues, Shi and Doherty (2008) examined the effects of reverberation and WDRC release time on sentence intelligibility using wearable hearing aids. Consistent with Reinhart et al. (2016), sentence intelligibility was significantly worse in reverberation; however, unlike Reinhart et al., Shi and Doherty did not find any effect of WDRC release time. The discrepancy between these two studies could be due to several methodological differences in implementing WDRC. The 2008 study used wearable hearing aids that manipulated other parameters of the compressor, including attack time, whereas Reinhart et al. used a hearing aid simulation, which fixed all WDRC parameters except for release time. In addition, Shi and Doherty implemented individualized compression ratios ranging from 1:1 to 4:1. The lower end of this range is effectively linear, which minimizes or negates the effect of the release time. Given the different study designs, it is difficult to conclude exactly what influence WDRC release time had on the findings.

An additional limitation of the two previous studies is they have not investigated any potential source of individual variability. Recent evidence suggests that cognitive ability may modulate how a listener responds to different WDRC release times. Working memory is one cognitive ability that has been shown to affect how individuals perceive speech that has been acoustically altered by hearing aids (e.g., Gatehouse, Naylor, & Elberling, 2003; Lunner, Rudner, & Rönnberg, 2009; Lunner & Sundewall-Thorén, 2007; Souza, Arehart, Shen, Anderson, & Kates, 2015). Working memory is a limited-capacity cognitive system engaged in the simultaneous processing and storage of information (Baddeley, 2000; Daneman & Carpenter, 1980; Miyake & Shah, 1999). A number of studies have demonstrated that individuals with higher working memory perform better with short WDRC release times in modulated noise whereas individuals with lower working memory perform better with long WDRC release times (Foo, Rudner, Rönnberg, & Lunner, 2007; Gatehouse et al., 2003; Lunner et al., 2009; Lunner & Sundewall-Thorén, 2007; Rudner, Foo, Rönnberg, & Lunner, 2009; Souza & Sirow, 2014). In these studies, it was hypothesized that individuals with higher working memory are able to benefit from the additional information provided by short WDRC release times without being affected by the resulting acoustic distortion in the same way that individuals with lower working memory are affected. Thus, working memory may be a point of division among individuals when it comes to determining optimal WDRC release time in reverberant environments. This is especially true given that WDRC release time significantly affects the signal acoustics even in the presence of reverberation (Reinhart et al., 2016). Thus, when examining optimal WDRC release time for reverberant environments in the real world, the role of individual working memory should be considered. Otherwise, a WDRC release time that is optimal in reverberation for one individual may not be most suitable for another individual on the basis of differences in working memory ability.

The purpose of the present study was to investigate the effects of reverberation and WDRC release time for speech intelligibility and clarity of sentences while additionally considering the effects of working memory. These relationships among reverberation, WDRC release time, and working memory were investigated by both objective (intelligibility) and subjective (clarity ratings) measures in a sentence recognition task. This study used a hearing aid simulation to isolate the effects of WDRC release time.

Method

Participants

Participants included 30 adults who were non–hearing aid users (mean age = 76.1 years, range 59 to 88 years; 12 men, 18 women). All participants presented with symmetrical mild to moderately-severe sloping sensorineural hearing loss. Air conduction thresholds were measured at 250–8000 Hz octave frequencies and inter-octaves at 3000 and 6000 Hz. Bone conduction testing was performed at octave frequencies 0.5–4.0 kHz. Sensorineural hearing loss was defined as presenting with no more than one air–bone gap greater than 10 dB in combination with normal tympanometry. Individual audiometric symmetry was defined as having no more than two inter-ear air conduction threshold gaps greater than 10 dB. All participants presented with immitance and tympanometric peak pressure within normal limits in both ears using a standard 226-Hz tone (Wiley et al., 1996). All participants reported good general health at the time of testing and no history of neurologic or otologic impairment. Participants had normal or corrected vision and reported no history of dyslexia or reading disability. Participants all spoke English as their sole or primary language. To screen for mild cognitive impairment, participants completed the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975). All participants received a passing score of 26 or higher (mean score = 28.8).

A post hoc power analysis revealed that the current number of participants provided a power of at least 0.727 for all interactions in the models used (repeated-measures analyses of variance [RM-ANOVAs]). All study procedures were reviewed and approved by the Northwestern University Institutional Review Board. Participants completed an informed consent process and were compensated for their time.

Working Memory

Individual working memory was assessed using an English-language version of the Reading Span Test (RST) originally developed by Rönnberg, Arlinger, Lyxell, & Kinnefors (1989). The RST was designed to simultaneously tax information processing (by requiring semantic judgments) and memory storage (by requiring recall of words from sentences).

The test materials consisted of 54 five-word sentences that were presented on a 26-in. computer monitor. Sentences were displayed at a rate of one word (e.g, *drove*) or word cluster (e.g., *the car*) per 0.8 s, and sentences were presented in sets ranging from three to six sentences per set. Participants were required to read the words aloud as they flashed across the screen and, at the end of a sentence, to make a semantic judgment about that sentence (i.e., yes, that sentence made sense, or no, that sentence did not make sense). At the end of each sentence set, participants were asked to recall, in correct serial order, the first or last word of each sentence within that set of sentences. This was done without the participants' knowledge of whether the first or the last word would be prompted prior to seeing the set of sentences. Whether the experimenter asked for the first or the last word of each sentence was pseudorandomized across the RST, such that first-word and last-word recall conditions occurred an equal number of times. The RST score was the percentage of first or last words correctly recalled by the test participant out of the 54 sentences.

On the basis of the results of the RST task, participants were separated into two groups: high and low working memory. Due to lack of large-scale normative data on the RST, individuals were divided into groups on the basis of a median split of the data (median = 37.97%). This split criterion is consistent with previous studies that have used criteria ranging from 36% to 44% in similar sample populations (e.g., Arehart, Souza, Baca, & Kates, 2013; Lunner, 2003). On the basis of this criterion, 15 participants were categorized as having high working memory (mean = 44.69%, range 38.9% to 55.6%), and 15 participants were categorized as having low working memory (mean = 30.37%, range 22.2% to 37.0%).

The groups were statistically analyzed to determine that there were no significant differences in hearing loss or age between the groups (see Results section for further details). Participant audiograms for both groups can be seen in Figure 1.

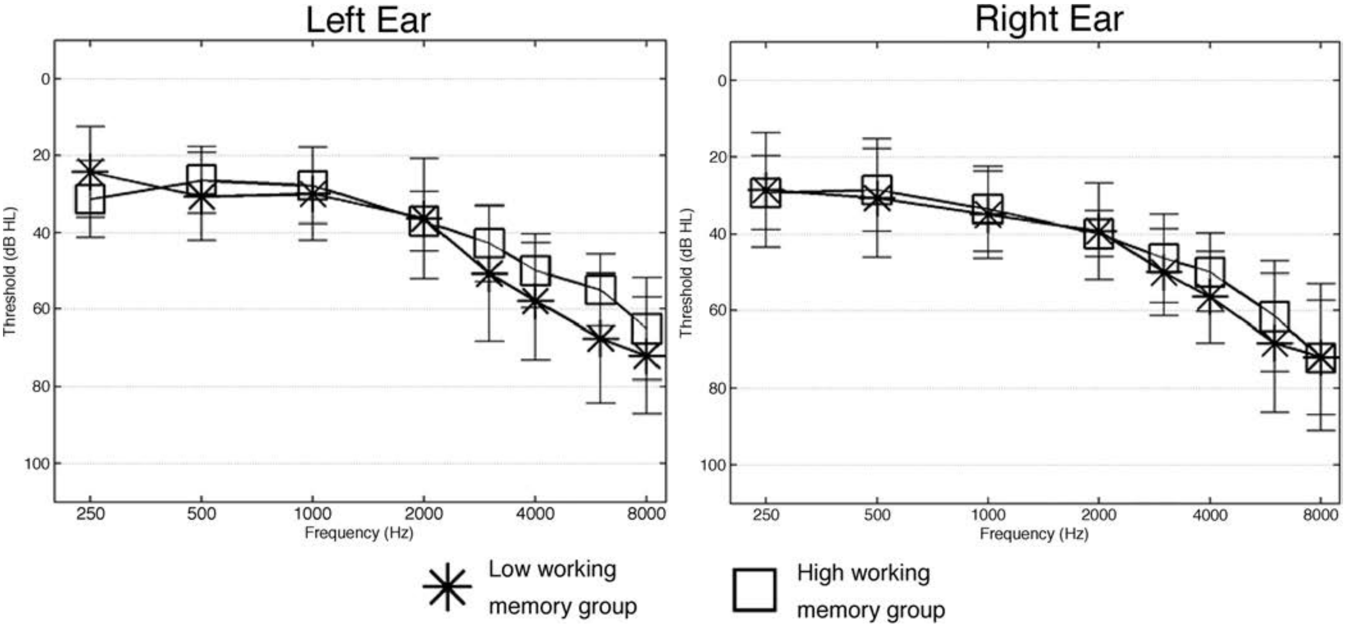
Stimuli

Speech stimuli consisted of 160 unique, low-context IEEE sentences ("IEEE Recommended Practice," 1969). Locally made recordings, controlled for differences in regional dialect, were produced by two female and two male talkers (McCloy, Wright, & Souza, 2015). These stimuli were chosen because they are more indicative of real-world listening than isolated speech segments, and having multiple talkers makes results more generalizable. In addition, the lengths of the sentence stimuli were more likely to tax working memory as well as to ensure that amplitude modulations in the signals would allow for dynamic engagement of the hearing aid WDRC processor simulation. The entire set of sentence stimuli was processed in two stages to yield the final stimulus set: (a) virtual reverberation simulator and (b) hearing aid compression simulator.

Virtual Reverberation Simulator

Broadband reverberation times of 0.0, 0.5, 1.0, 2.0, and 4.0 s were simulated using a method developed by

Figure 1. Mean air-conduction thresholds for each working memory group for the left and right ears. Error bars represent ± 1 *SD*



Zahorik (2009). In brief, the simulation used an image model to compute directions, delays, and attenuations of the early reflections. Early reflections were spatially rendered along the direct path using non-individualized, head-related transfer functions using an image method (Allen & Berkley, 1979). The late reverberant energy was simulated statistically using exponentially decaying Gaussian noise. The model allowed for the manipulation of room dimension, the position of the source and listener, and the absorptive properties of reflective surfaces. Overall, this method provides greater experimental control and flexibility than real room recordings while producing reverberant signals that are reasonable physical and perceptual approximations of those measured in real rooms (Zahorik, 2009).

In the present simulation, room size and source–listener distance were fixed, and the absorptive properties of the reflective surfaces were varied. Room size was fixed at 5.7 m × 4.3 m × 2.6 m, and source–listener distance was fixed at 1.4 m. Absorptive properties were varied to yield a range of reverberation times: 0.0, 0.5, 1.0, 2.0, and 4.0 s. This range of reverberation times was selected to approximate a range of listening conditions experienced in real environments.

Hearing Aid Compression Simulator

WDRC using release time values of 12, 90, 800, and 1,500 ms was simulated using a Matlab-based hearing aid simulation developed by Kates (2008). In brief, the simulation method consisted of two basic stages. The first stage included six-channel nonlinear processing and spectral equalization to approximate the effects of digital signal processing occurring within the hearing aid. The second stage included linear filtering to approximate the effects of the receiver, tubing, and ear canal acoustics. This simulation method allowed for the manipulation of input speech level, compression threshold, compression ratio, attack time, and release time. Overall, this method provided further experimental control while still accurately simulating real hearing aid processing (Arehart, Kates, & Anderson, 2010).

In the present simulation, to isolate the effects of WDRC release time, all other parameters were fixed. The input speech level was 65 dB SPL. The compression threshold was set at 45 dB SPL, and a compression ratio of 3:1 was used across all six available channels. A fixed compression ratio was implemented to ensure that all participants experienced similar WDRC conditions. The 3:1 ratio was selected because it represents the upper range of ratios implemented in wearable hearing aids. The attack time was fixed at 10 ms. Stimuli were processed with release times of 12, 90, 800, and 1,500 ms. These release time values represent a range from short (12 ms) to long (1,500 ms) implemented in commercial hearing aids.

Procedure

All listeners completed speech testing for each of the 20 test conditions (5 Reverberation Times × 4 WDRC Release Times). Speech testing took place in a double-walled sound booth, and digital signals were converted to analog by Tucker-Davis Technologies equipment (RX6, Alachusa, FL) and played through Etymotic-ER2 insert phones (Elk Grove Village, IL). Stimuli were separated into four blocks on the basis of release time, and reverberation times were randomized within each block. The order of the four blocks was randomized for each participant.

Sentences were presented binaurally at 65 dB SPL to represent a conversational speech level. Participants received individual NAL-NL1 shaping to mimic the individualized frequency shaping provided by wearable hearing aids (Byrne, Dillon, Ching, Katsch, & Keidser, 2001). Sentence audibility was verified by using a sound level meter to record amplified speech output for the average participant audiogram (see Figure 1). Average one-third octave band levels for multiple sentences were compared with average audiometric thresholds converted to dB SPL. Recorded levels exceeded threshold levels for octave frequencies from 500 to 4000 Hz. In this way, we confirmed that NAL-NL1 frequency shaping was providing sufficient audibility for participants across the frequency range of speech. See supplemental materials for graphs plotting speech level alongside average patient audiogram (converted to dB SPL) and alongside the audiogram of the participant who had the most hearing loss. Stimulus presentation and scoring were controlled by a locally developed Matlab program. There were two outcome measures considered to assess the effects of reverberation and WDRC release time: intelligibility and clarity.

Intelligibility

Immediately following stimulus presentation, participants were asked to repeat back the sentence they heard. Sentences were scored on the basis of the number of key words (five per sentence) reproduced correctly. Word reproductions that contained a single morpheme substitution, addition, or subtraction were marked correct (e.g., *tests* was accepted for *tested*). However, semantically significant morpheme alterations (e.g., *girl* for *girlfriend*) and irregular form changes (e.g., *feels* for *felt*) were marked incorrect. Scoring was performed by a single scorer to ensure rule consistency.

Clarity

Following sentence recall, participants were asked to rate the clarity of the sentence. Rating was conducted on a 7-point Likert scale (1 = *completely unclear*, 2 = *unclear*, 3 = *somewhat unclear*, 4 = *neither clear nor unclear*, 5 = *somewhat clear*, 6 = *clear*, 7 = *completely clear*). Clarity was assessed because it has been shown to be the largest contributing factor in determining overall sound quality, which is an important subjective dimension for quantifying hearing aid benefit (e.g., Eisenberg, Dirks, Takayanagi, & Martinez, 1998; Preminger & Van Tasell, 1995).

Results

Verifying Group Equivalency in Age and Hearing Thresholds

Analyses were performed to verify that the two working memory groups were not significantly different in age or hearing loss. Thus, between-groups differences on the primary speech tasks would be attributable to differences in working memory. An independent-samples t test found no significant difference in participant age between the groups, $t(28) = 1.141$, $p = .263$.

In addition, both groups had similar average audiograms. This was confirmed with separate RM-ANOVAs for each ear with frequency as a within-subject factor and working memory group as between-subjects factor. Both RM-ANOVAs had a statistically significant main effect of frequency: left ear, $F(7, 22) = 29.923$, $p < .001$, $\eta_p^2 = .905$; right ear, $F(7, 22) = 19.76$, $p < .001$, $\eta_p^2 = .863$. This is unsurprising given the sloping, high-frequency hearing loss of the participants. The main effect of working memory group was not significant for either ear, which indicates that the groups has similar degrees of hearing loss: left ear, $F(1, 28) = 3.63$, $p = .067$, $\eta_p^2 = .115$; right ear, $F(1, 28) = 2.636$, $p = .116$, $\eta_p^2 = .086$. Nor was there a significant Frequency × Working Memory group interaction in either ear, which indicates that the groups had similar audiometric configurations: left ear, $F(7, 22) = 1.317$, $p = .289$, $\eta_p^2 = .295$; right ear, $F(7, 22) = 0.385$, $p = .901$, $\eta_p^2 = .109$.

Intelligibility Results

In order to equalize variance across the performance range, percentage correct scores were converted to rationalized arcsine units for statistical analyses (Studebaker, 1985). A three-way RM-ANOVA was conducted with two within-subject factors (reverberation and WDRC release time) and one between-subjects factor (working memory group). Main effect and interaction results are depicted in Table 1. Results can be seen in Figure 2. There were significant main effects for all three factors. To further explore these main effects, pairwise comparisons were conducted using a Bonferroni correction to control for multiple comparisons.

Increasing reverberation time significantly decreased sentence intelligibility scores for all pairwise comparisons ($p < .001$). The only significant difference among the WDRC release times was that performance was better with the longest release time (1,500 ms) than the shortest release time (12 ms; $p = .009$). However, due to the presence of higher-order interactions, these results are qualified as detailed below.

Reverberation × WDRC Release Time

The interaction between reverberation and WDRC release time ($p = .048$) was such that the difference among WDRC release times increased as a function of the amount of reverberation within a signal. To further examine this interaction, separate one-way RM-ANOVAs were calculated for each reverberation time with WDRC release time as the within-subject factor. Results of these analyses can be seen in Table 2. The difference among WDRC release times tended to reach significance and have larger effect sizes under the more reverberant conditions. These results suggest that individuals perform better with longer release times; however, this effect tended to only reach significance in reverberant conditions (i.e., starting at 0.5 s).

Table 1. Results of three-way repeated-measures analysis of variance on rationalized arcsine units of intelligibility.

		Degrees of freedom	*F* value	*p* value	partial η^2
Main effects	**Reverberation**	**(4, 25)**	**50.483**	**< .001**	**.890**
	WDRC release time	**(3, 26)**	**3.981**	**.019**	**.315**
	Working memory	**(1, 28)**	**9.774**	**.004**	**.259**
Two-way interactions	**Reverberation × WDRC Release Time**	**(12, 17)**	**2.402**	**.048**	**.629**
	WDRC Release Time × Working Memory	(3, 26)	2.720	.065	
	Reverberation × Working Memory	**(4, 25)**	**2.668**	**.036**	**.087**
Three-way interaction	Reverberation × WDRC Release Time × Working Memory	(12, 17)	1.073	.382	

Note. Significant findings are marked in bold. WDRC = wide dynamic range compression.

Reverberation × Working Memory

There was also a significant Reverberation × Working Memory interaction ($p = .036$). Speech intelligibility decreased as a function of reverberation time for individuals in both the high and low working memory groups. The rate of decline was more precipitous for the low working memory group across reverberation times. To further examine this interaction, we calculated how each individual's intelligibility decreased as a function of increasing reverberation relative to his or her baseline intelligibility. This was done by subtracting intelligibility performance in the condition without any reverberation (0.0 s) from intelligibility performance in each of the reverberation conditions (0.5, 1.0, 2.0, and 4.0 s). Results can be seen in Figure 3. Pairwise *t* tests were conducted using a Bonferroni correction comparing the rate of performance decline between the two working memory groups. In the 0.5-s reverberation time, the groups were not significantly different from one another ($p = .898$). However, there were significant differences between the groups in the 1.0 s ($p = .017$), 2.0 s ($p = .026$), and 4.0 s ($p = .037$) conditions. These results suggest that reverberation hinders speech intelligibility for all individuals; however, this effect is more pronounced for the group with lower working memory.

Clarity Results

A similar three-way RM-ANOVA was conducted with two within-subject factors (reverberation and WDRC release time) and one between-subjects factor (working memory group) with absolute clarity rating as the dependent variable. Main effect and interaction results are depicted in Table 3. Results can be seen in Figure 4. There were significant main effects for both reverberation ($p < .001$) and WDRC release time ($p = .045$). To further explore these main effects, pairwise comparisons were made using a Bonferroni correction to control for multiple comparisons.

Increasing reverberation time significantly decreased sentence clarity ratings for all pairwise comparisons ($p < .001$) except between the 0.0- and 0.5-s conditions, which

Figure 2. Speech intelligibility scores of sentence stimuli at five different reverberation times for four different release time processing conditions. The error bars represent ± 1 standard error.

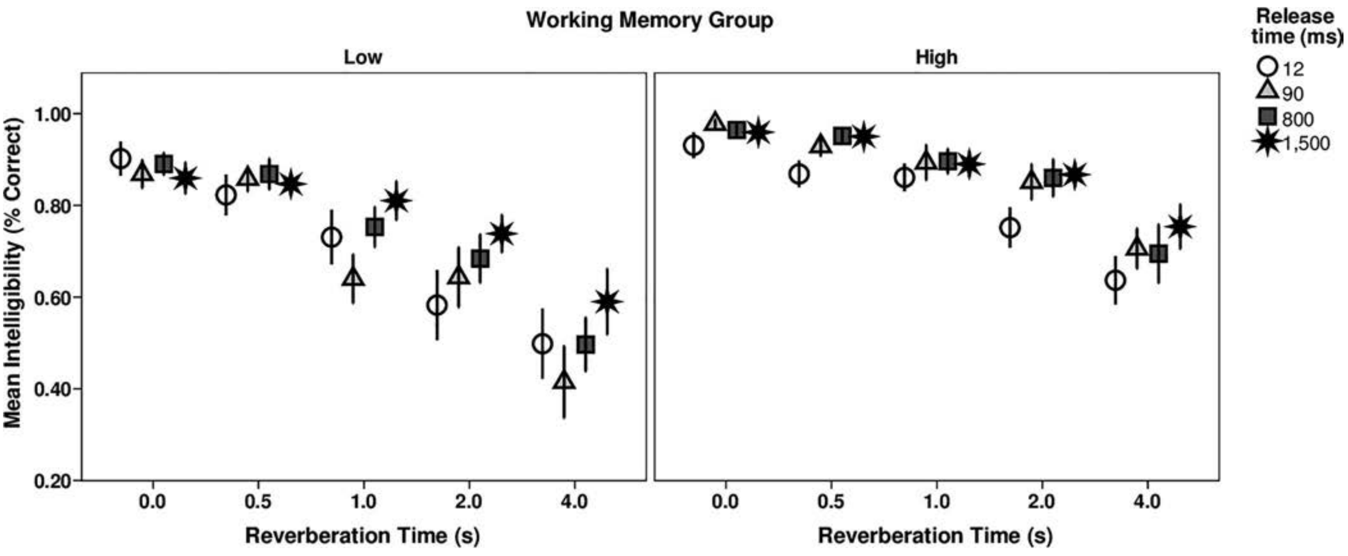


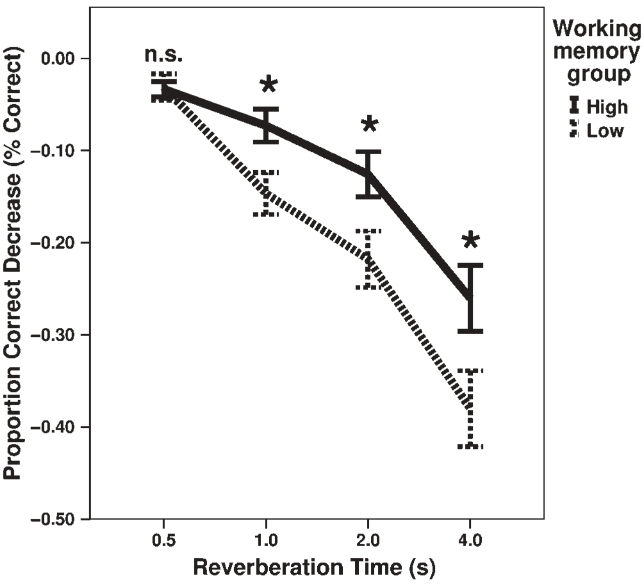
Table 2. Results of post hoc analyses of variance investigating the effect of wide dynamic range compression release time for each reverberation time on rationalized arcsine unit–transformed intelligibility scores.

Reverberation time	Degrees of freedom	*F* value	*p* value	partial η^2
0.0 s	(3, 27)	0.439	.727	.043
0.5 s	(3, 27)	3.105	.043	.256
1.0 s	(3, 27)	2.100	.124	.189
2.0 s	(3, 27)	4.487	.011	.333
4.0 s	(3, 27)	4.132	.016	.315

approached significance (p = .078). The only significant difference among the WDRC release times was that sentences processed with the 1,500-ms release time was rated significantly higher than the 90-ms release time (p = .007). In addition, there was a significant Reverberation × WDRC Release Time interaction, which qualifies these results.

Similar to the intelligibility results, the interaction between reverberation and WDRC release time (p = .018) was such that the difference among WDRC release times increased as a function of the amount of reverberation within a signal. To further examine this interaction, separate one-way RM-ANOVAs were calculated for each reverberation time with WDRC release time as the within-subject factor. Results of these analyses can be seen in Table 4. These results were similar to the intelligibility results in that the difference among WDRC release times tended to reach significance and have larger effect sizes under the more reverberant conditions.

Figure 3. Speech intelligibility decrease as a function of reverberation time relative to performance in the anechoic condition (0.0 s) for each working memory group. The error bars represent ± 1 standard error. Asterisks represent a significant difference between the two groups at the given reverberation time (p < .05).



Discussion

The present study evaluated the relationships among reverberation, WDRC release time, and individual working memory on measures of sentence intelligibility and clarity in individuals with hearing impairment. The following are the general findings of the analyses. Overall, speech intelligibility and clarity decreased as the amount of reverberation increased. Moreover, the low working memory group was more affected by increasing reverberation. Last, speech intelligibility and clarity decreased with shorter time constants; however, there was an interaction between reverberation and WDRC release time for both intelligibility and clarity. Each of these findings is discussed in further detail below.

Consistent with previous literature, speech intelligibility for individuals with hearing impairment decreased in the presence of even mild amounts of reverberation (i.e., 0.5 s). This reverberation time is representative of many real-world listening environments, such as restaurants or living spaces. As such, clinicians and researchers should be aware of reverberation and how the presence of reverberation might modulate the listener experience for individuals with hearing impairment outside of the clinic or laboratory. In a clinical sense, this supports the use of speech perception tests that incorporate realistic reverberation when assessing patient impairment in the real world (e.g., Brungart, Sheffield, & Kubli, 2014; Spitzer, Sandridge, Newman, Sydlowski, & Ghent, 2015). As it pertains to translational research, individuals should be aware as to how reverberation might affect the signal acoustics and how that will affect the generalizability of results in the real world (Bradley, Reich, & Norcross, 1999; Houtgast & Steeneken, 1985; Reinhart et al., 2016).

It is interesting to note that not all individuals were equally affected by reverberation. In the present study, individuals with lower working memory experienced a more precipitous decline in speech intelligibility as a function of reverberation (see Figure 3). This finding supports the hypothesis that working memory provides a form of cognitive compensation in cases of degraded speech acoustics (Rönnberg et al., 2013; Rönnberg, Rudner, Foo, & Lunner, 2008; Stenfelt & Rönnberg, 2009). This relationship between working memory and resistance to acoustic distortion has been demonstrated in background noise (Lunner & Sundewall-Thorén, 2007; Rudner, Rönnberg, & Lunner, 2011) and rapid speech (Vaughan, Storzbach, & Furukawa, 2006; Wingfield, Tun, Koh, & Rosen, 1999); however, this is the first study, to the authors' knowledge, to empirically demonstrate this paradigm with reverberant distortion. Although it should be noted that attention and cognitive compensation might preserve speech intelligibility in degraded conditions in the short term (Halin, Marsh, Hellman, Hellström, & Sörqvist, 2014), this heightened cognitive expenditure may lead to increased mental fatigue in listeners (Bess & Hornsby, 2014; Hornsby, 2013).

Consistent with previous findings investigating nonsense syllables, individuals in the present study performed significantly better in reverberation with longer WDRC

Table 3. Results of three-way repeated-measures analysis of variance on clarity rating.

		Degrees of freedom	*F* value	*p* value	partial η^2
Main effects	**Reverberation**	**(4, 25)**	**100.071**	**< .001**	**.941**
	WDRC release time	**(3, 26)**	**4.822**	**.008**	**.357**
	Working memory	(1, 28)	2.833	.103	
Two-way interactions	**Reverberation × WDRC Release Time**	**(12, 17)**	**3.060**	**.018**	**.684**
	WDRC Release Time × Working Memory	(3, 26)	0.479	.700	
	Reverberation × Working Memory	(4, 25)	0.471	.757	
Three-way interaction	Reverberation × WDRC Release Time × Working Memory	(12, 17)	1.250	.328	

Note. Significant findings are marked in bold. WDRC = wide dynamic range compression.

release times. This finding is an expansion upon the previous study of nonsense syllables and is presumably driven by the additive distortion occurring to the temporal envelope as a result of short WDRC release times (Reinhart et al., 2016). However, unlike in the previous study examining nonsense syllables, in the present study the effect of WDRC release time increased as the amount of reverberation increased (see Tables 2 and 4). This discrepancy is likely due to differences in stimuli. Sentence stimuli are longer and likely to have sufficient duration to more fully interact with the fluctuations of the WDRC circuit than nonsense syllables. Because sentences are more indicative of real-world listening, the conclusion from the present study that WDRC release time has an even larger effect in the presence of reverberation is more likely to persist in realistic listening environments.

The greater effect of WDRC release time on speech intelligibility and clarity in increasing reverberation could be due to several reasons. As previously discussed, top-down processing can be recruited to compensate for the effects of signal degradation. This cognitive compensation hypothesis states that individuals have a limited pool of cognitive resources largely independent of modality (Pichora-Fuller & Singh, 2006; Rudner & Lunner, 2013). Increasing task demand, such as in the case of distorted speech processing, requires a larger proportion of these available resources. As the required resources for a given task approach individual capacity limits, individuals are not able to increase top-down processing to further compensate for signal distortion. Applying this to the present findings, recall that reverberation and short WDRC release times cause additive distortion to the temporal envelope of a speech signal (Reinhart et al.,

Figure 4. Clarity scores of sentence stimuli at five different reverberation times for four different release time processing conditions. The error bars represent ± 1 standard error.

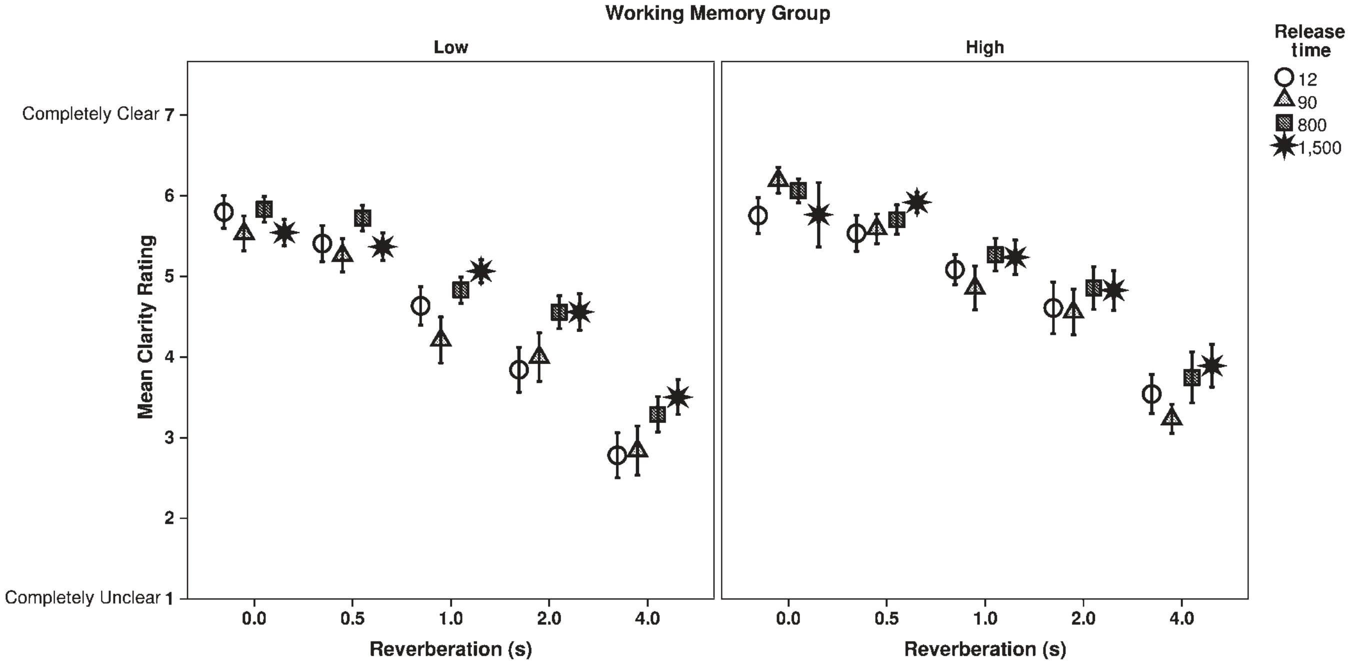


Table 4. Results of post hoc analyses of variance investigating the effect of wide dynamic range compression release time for each reverberation time on sentence clarity.

Reverberation time	Degrees of freedom	*F* ratio	*p* value	partial η^2
0.0 s	(3, 27)	0.922	.434	.031
0.5 s	(3, 27)	1.713	.170	.056
1.0 s	(3, 27)	5.560	.002	.161
2.0 s	(3, 27)	5.810	.001	.167
4.0 s	(3, 27)	7.334	< .001	.202

2016). In addition, age and hearing loss already require compensatory top-down processing of speech (Alain, McDonald, Ostroff, & Schneider, 2004; Pichora-Fuller, Schneider, & Daneman, 1995). Thus, it may be that the additional distortion introduced by short WDRC release times overloads the cognitive compensation mechanism (i.e., task demand surpasses available cognitive resources) when listeners are already being taxed by aging, hearing loss, and reverberation. This hypothesis could account for the findings presently observed.

In addition, there is a possible acoustic hypothesis for the interaction between WDRC release time and reverberation. Although reverberation does cause some distortion to the temporal envelope, it predominantly attenuates the higher modulation frequencies of a signal (Houtgast & Steeneken, 1985). WDRC in hearing aids, on the other hand, principally distorts the slow modulation cues present in the temporal envelope (Souza, 2002). In an undistorted signal, listeners have access to both the slow and fast modulation cues; thus, the effects of temporal envelope distortion by short WDRC release times may have minimal effect because listeners can use the higher modulation rate cues to compensate. However, when the fast modulation cues are distorted as a result of reverberation, WDRC release time may have a greater effect. In other words, in instances in which reverberation is already removing some of the cues, the use of short WDRC release times may be reducing listener access to the one cue remaining. This may be especially true given the increased dependence older listeners with hearing impairment have on temporal envelope cues (Fogerty & Humes, 2011, 2012).

All individuals, regardless of working memory, benefited from longer WDRC release times in reverberation. Thus, optimal WDRC release time in reverberation does not seem to vary on the basis of listener working memory characteristics. Although differences exist among these studies as to how individual cognition was defined and classified, the finding of improved performance with WDRC in reverberation is in contrast with the background noise and WDRC literature previously discussed. Recall that in modulated background noise, individuals with higher working memory perform better with short WDRC release times, whereas individuals with lower working memory perform better with long WDRC release times (Foo et al., 2007; Gatehouse et al., 2003; Lunner et al., 2009; Lunner & Sundewall-Thorén, 2007; Rudner et al., 2009; Souza & Sirow, 2014). These findings, in combination with the present study, suggest that individuals with lower working memory should be fit with long WDRC release times across a variety of acoustic environments. On the other hand, individuals with higher working memory may benefit most from short WDRC release times in situations dominated by background noise (e.g., a restaurant) and long WDRC release times in situations dominated by reverberation (e.g., lecture hall or sanctuary). Although further research is necessary to validate these findings in a clinical context, as well as to examine the combined effects of reverberation and background noise, these early findings suggest an interesting possibility in situation-variable WDRC settings for some individuals.

In general, the subjective clarity results corroborate the conclusions of the intelligibility analyses. There were significant interactions between reverberation and WDRC release time for both measures, indicating that WDRC release time has a larger effect under reverberant conditions. However, there were also discrepancies between the two measures. For subjective clarity, reverberation affected listener perception of speech clarity equally for both groups, despite the finding that reverberation affected intelligibility of individuals with lower working memory more severely. These findings are consistent with previous research that although generally correlated, clarity and intelligibility measures may differ from each other (e.g., Eisenberg et al., 1998). This suggests that subjective measures, such as clarity, may not be as sensitive to small effects as more objective measures. Nonetheless, subjective measures remain an important dimension in assessing hearing aid benefit because they give insight into what individuals might be aware of regarding their ability to hear and communicate, associated with their signal processing.

Limitations

These results contribute to a theoretical understanding of WDRC settings for individuals in reverberant environments. However, some aspects of the research design may limit generalizability of findings to the clinic. First, the participants in the present study were non–hearing aid users without prior experience with WDRC. This sample emulates an individual coming in for his or her first hearing aid fitting with nonlinear processing; however, it is unclear what effect prior experience and acclimatization with WDRC will have on this paradigm. Previous work (Foo et al., 2007; Rudner et al., 2009) has suggested any acclimatization will be minimal, but those studies did not specifically consider use of WDRC in reverberant environments.

A second limitation pertains to the reverberation method used to process the stimuli. Overall, the simulation method used is well validated (Zahorik, 2009). However, in the present implementation, the absorption coefficients were varied, and room size was fixed. Although long reverberation times may occur in rooms of the size simulated (e.g., a hard-tiled bathroom), longer reverberation times are typically found in larger spaces. The change in room dimension would likely result in different directions, delays, and attenuations of the reflected energy across frequencies.

Last, the WDRC compression ratio was generally higher than that which would be fit for individuals with mild-to-moderate hearing loss. The present study implemented a 3:1 compression ratio, which represents the upper limit of (nominal) compression ratios that might be implemented in wearable hearing aids. For a dynamic signal, the effective compression ratio would be somewhat lower (Stone & Moore, 1992). Previous studies have demonstrated that high compression ratios augment the effect that WDRC release time has on a signal (Neuman, Bakke, Mackersie, Hellman, & Levitt, 1998). It is possible that lower levels of compression would be less disruptive, and the subsequent effect of release time would be diminished. Whether the effects of WDRC release time observed in the present study persist under more moderate compression ratios requires further study.

Conclusions

In the present study, we examined the relationships among reverberation, WDRC release time, and working memory on sentence intelligibility and clarity. Reverberation decreased speech intelligibility for all listeners; however, for individuals with lower working memory, speech intelligibility decreased at a more precipitous rate as a function of reverberation time, compared with individuals with higher working memory. Regardless of their working memory, individuals performed significantly better with longer release times, and this effect was larger in greater amounts of reverberation. This suggests that individuals may perform better in reverberation with longer WDRC release times; however, it is not known if this effect will persist at lower, individualized compression ratios. Results of the clarity measure mostly followed the trends of the intelligibility results; however, clarity was not sensitive to group differences between the high and low working memory groups. Last, listeners ranked longer WDRC release times as significantly more clear.

Acknowledgments

Work is supported by National Institutes of Health Grants R01 DC0060014 and R01 DC012289 and the American Speech-Language-Hearing Foundation. The authors thank James Kates for providing the compression simulation, Pavel Zahorik for providing the virtual reverberation simulation, Nirmal Srinivasan for processing the reverberation stimuli, and Laura Mathews for help with data collection. Portions of this work were presented at the Conference on Cognitive Hearing Science for Communication, Linköping, Sweden, June 2015.

References

Alain, C., McDonald, K. L., Ostroff, J. M., & Schneider, B. (2004). Aging: A switch from automatic to controlled processing of sounds? *Psychology and Aging, 19,* 125–133.

Allen, J. B., & Berkley, D. A. (1979). Image model for efficiently modeling small–room acoustics. *The Journal of the Acoustical Society of America, 65,* 943–950.

Arehart, K. H., Kates, J. M., & Anderson, M. C. (2010). Effects of noise, nonlinear processing, and linear filtering on perceived speech quality. *Ear and Hearing, 31,* 420–436.

Arehart, K. H., Souza, P., Baca, R., & Kates, J. M. (2013). Working memory, age and hearing loss: Susceptibility to hearing aid distortion. *Ear and Hearing, 34,* 251–260.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4,* 417–423.

Bess, F. H., & Hornsby, B. W. (2014). Commentary: Listening can be exhausting—Fatigue in children and adults with hearing loss. *Ear and Hearing, 35,* 592–599.

Bradley, J. S., Reich, R. D., & Norcross, S. G. (1999). On the combined effects of signal-to-noise ratio and room acoustics on speech intelligibility. *The Journal of the Acoustical Society of America, 106,* 1820–1828.

Brungart, D. S., Sheffield, B. M., & Kubli, L. R. (2014). Development of a test battery for evaluating speech perception in complex listening environments. *The Journal of the Acoustical Society of America, 136,* 777–790.

Byrne, D., Dillon, H., Ching, T., Katsch, R., & Keidser, G. (2001). NAL-NL1 procedure for fitting nonlinear hearing aids: Characteristics and comparisons with other procedures. *Journal of the American Academy of Audiology, 12,* 37–51.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–466.

Duquesnoy, A. J., & Plomp, R. (1980). Effect of reverberation and noise on the intelligibility of sentences in cases of presbycusis. *The Journal of the Acoustical Society of America, 68,* 537–544.

Eisenberg, L. S., Dirks, D. D., Takayanagi, S., & Martinez, A. S. (1998). Subjective judgments of clarity and intelligibility for filtered stimuli with equivalent speech intelligibility index predictions. *Journal of Speech, Language, and Hearing Research, 41,* 327–339.

Festen, J. M., & Plomp, R. (1983). Relations between auditory functions in impaired hearing. *The Journal of the Acoustical Society of America, 73,* 652–662.

Fitzgibbons, P. J., & Wightman, F. L. (1982). Gap detection in normal and hearing-impaired listeners. *The Journal of the Acoustical Society of America, 72,* 761–765.

Florentine, M., & Buus, S. (1984). Temporal gap detection in sensorineural and simulated hearing impairments. *Journal of Speech and Hearing Research, 27,* 449–455.

Fogerty, D., & Humes, L. E. (2011). Envelope and temporal fine structure perceptual weights for sentences: Effect of age, hearing loss, and amplification. *The Journal of the Acoustical Society of America, 130,* 2448.

Fogerty, D., & Humes, L. E. (2012). The role of vowel and consonant fundamental frequency, envelope, and temporal fine structure cues to the intelligibility of words and sentences. *The Journal of the Acoustical Society of America, 131,* 1490–1501.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12,* 189–198.

Foo, C., Rudner, M., Rönnberg, J., & Lunner, T. (2007). Recognition of speech in noise with new hearing instrument compression release settings requires explicit cognitive storage and processing capacity. *Journal of the American Academy of Audiology, 18,* 618–631.

Fortune, T. W., Woodruff, B. D., & Preves, D. A. (1994). A new technique for quantifying temporal envelope contrasts. *Ear and Hearing, 15,* 93–99.

Gatehouse, S., Naylor, G., & Elberling, C. (2003). Benefits from hearing aids in relation to the interaction between the user and the environment. *International Journal of Audiology, 42*(Suppl. 1), S77–S85.

Gopinath, B., Schneider, J., Hickson, L., McMahon, C. M., Burlutsky, G., Leeder, S. R., & Mitchell, P. (2012). Hearing handicap, rather than measured hearing impairment, predicts poorer quality of life over 10 years in older adults. *Maturitas, 72,* 146–151.

Gordon-Salant, S., & Fitzgibbons, P. J. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech and Hearing Research, 36,* 1276–1285.

Gordon-Salant, S., & Fitzgibbons, P. J. (1995). Comparing recognition of distorted speech using an equivalent signal-to-noise ratio index. *Journal of Speech and Hearing Research, 38,* 706–713.

Halin, N., Marsh, J. E., Hellman, A., Hellström, I., & Sörqvist, P. (2014). A shield against distraction. *Journal of Applied Research in Memory and Cognition, 3,* 31–36.

Halling, D. C., & Humes, L. E. (2000). Factors affecting the recognition of reverberant speech by elderly listeners. *Journal of Speech, Language, and Hearing Research, 43,* 414–431.

Henning, R. L. W., & Bentler, R. A. (2008). The effects of hearing aid compression parameters on the short-term dynamic range of continuous speech. *Journal of Speech, Language, and Hearing Research, 51,* 471–484.

Hopkins, K., & Moore, B. C. (2007). Moderate cochlear hearing loss leads to a reduced ability to use temporal fine structure information. *The Journal of the Acoustical Society of America, 122,* 1055–1068.

Hopkins, K., & Moore, B. C. (2011). The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *The Journal of the Acoustical Society of America, 130,* 334–349.

Hornsby, B. W. (2013). The effects of hearing aid use on listening effort and mental fatigue associated with sustained speech processing demands. *Ear and Hearing, 34,* 523–534.

Houtgast, T., & Steeneken, H. J. (1985). A review of the MTF concept in room acoustics and its use for estimating speech intelligibility in auditoria. *The Journal of the Acoustical Society of America, 77,* 1069–1077.

Humes, L. E., & Christopherson, L. (1991). Speech identification difficulties of hearing-impaired elderly persons: The contributions of auditory processing deficits. *Journal of Speech and Hearing Research, 34,* 686–693.

IEEE recommended practice for speech quality measurements. (1969). *IEEE Transactions on Audio and Electroacoustics, 17,* 225–246.

Jenstad, L. M., & Souza, P. E. (2005). Quantifying the effect of compression hearing aid release time on speech acoustics and intelligibility. *Journal of Speech, Language, and Hearing Research, 48,* 651–667.

Kates, J. M. (2008). Signal processing basics. In *Digital hearing aids* (pp. 221–262). San Diego, CA: Plural.

Kochkin, S. (2000). MarkeTrak V: "Why my hearing aids are in the drawer": The consumers' perspective. *The Hearing Journal, 53,* 34–36.

Kochkin, S. (2010). MarkeTrak VIII: Consumer satisfaction with hearing aids is slowly increasing. *The Hearing Journal, 63,* 19–20.

Leek, M. R., & Summers, V. (1993). Auditory filter shapes of normal-hearing and hearing-impaired listeners in continuous broadband noise). *The Journal of the Acoustical Society of America, 94,* 3127–3137.

Lorenzi, C., Gilbert, G., Carn, H., Garnier, S., & Moore, B. C. (2006). Speech perception problems of the hearing impaired reflect inability to use temporal fine structure. *Proceedings of the National Academy of Sciences of the United States of America, 103,* 18866–18869.

Lunner, T. (2003). Cognitive function in relation to hearing aid use. *International Journal of Audiology, 42*(Suppl. 1), S49–S58.

Lunner, T., Rudner, M., & Rönnberg, J. (2009). Cognition and hearing aids. *Scandinavian Journal of Psychology, 50,* 395–403.

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. *Journal of the American Academy of Audiology, 18,* 604–617.

Marrone, N., Mason, C. R., & Kidd, G., Jr. (2008). The effects of hearing loss and age on the benefit of spatial separation between multiple talkers in reverberant rooms. *The Journal of the Acoustical Society of America, 124,* 3064–3075.

McCloy, D. R., Wright, R. A., & Souza, P. E. (2015). Talker versus dialect effects on speech intelligibility: A symmetrical study. *Language and Speech, 58,* 371–386.

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* New York, NY: Cambridge University Press.

Nelson, D. A., & Freyman, R. L. (1987). Temporal resolution in sensorineural hearing-impaired listeners. *The Journal of the Acoustical Society of America, 81,* 709–720.

Neuman, A. C., Bakke, M. H., Mackersie, C., Hellman, S., & Levitt, H. (1998). The effect of compression ratio and release time on the categorical rating of sound quality. *The Journal of the Acoustical Society of America, 103,* 2273–2281.

Peters, R. W., & Moore, B. C. (1992). Auditory filter shapes at low center frequencies in young and elderly hearing-impaired subjects. *The Journal of the Acoustical Society of America, 91,* 256–266.

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *The Journal of the Acoustical Society of America, 97,* 593–608.

Pichora-Fuller, M. K., & Singh, G. (2006). Effects of age on auditory and cognitive processing: Implications for hearing aid fitting and audiologic rehabilitation. *Trends in Amplification, 10,* 29–59.

Preminger, J. E., & Van Tasell, D. J. (1995). Measurement of speech quality as a tool to optimize the fitting of a hearing aid. *Journal of Speech and Hearing Research, 38,* 726–736.

Reinhart, P., & Souza, P. (2015, March). *Coping with reverberation: Characterizing patient disability in reverberant environments.* Paper presented at the American Academy of Audiology Conference, San Antonio, TX.

Reinhart, P. N., Souza, P. E., Srinivasan, N. K., & Gallun, F. J. (2016). Effects of reverberation and compression on consonant identification in individuals with hearing impairment. *Ear and Hearing, 37,* 144–152.

Rönnberg, J., Arlinger, S., Lyxell, B., & Kinnefors, C. (1989). Visual evoked potentials relation to adult speechreading and cognitive function. *Journal of Speech and Hearing Research, 32,* 725–735.

Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B., . . . Rudner, M. (2013). The ease of language understanding (ELU) model: Theoretical, empirical, and clinical advances. *Frontiers in Systems Neuroscience, 7,* 31. doi:10.3389/fnsys.2013.00031

Rönnberg, J., Rudner, M., Foo, C., & Lunner, T. (2008). Cognition counts: A working memory system for ease of language understanding (ELU). *International Journal of Audiology, 47*(Suppl. 2), S99–S105.

Rosen, S. (1992). Temporal information in speech: Acoustic, auditory and linguistic aspects. *Philosophical Transactions of the Royal Society B: Biological Sciences, 336,* 367–373.

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. *Scandinavian Journal of Psychology, 50,* 405–418.

Rudner, M., & Lunner, T. (2013). Cognitive spare capacity as a window on hearing aid benefit. *Seminars in Hearing, 34,* 298–307.

Rudner, M., Rönnberg, J., & Lunner, T. (2011). Working memory supports listening in noise for persons with hearing impairment. *Journal of the American Academy of Audiology, 22,* 156–167.

Shi, L. F., & Doherty, K. A. (2008). Subjective and objective effects of fast and slow compression on the perception of reverberant speech in listeners with hearing loss. *Journal of Speech, Language, and Hearing Research, 51,* 1328–1340.

Spitzer, J. B., Sandridge, S. A., Newman, C. W., Sydlowski, S., & Ghent, R. M., Jr. (2015). A speech perception test in simulated reverberation conditions. *American Journal of Audiology, 24,* 169–177.

Souza, P. E. (2002). Effects of compression on speech acoustics, intelligibility, and sound quality. *Trends in Amplification, 6,* 131–165.

Souza, P. E., Arehart, K. H., Shen, J., Anderson, M., & Kates, J. M. (2015). Working memory and intelligibility of hearing-aid processed speech. *Frontiers in Psychology, 6,* 526.

Souza, P. E., & Sirow, L. (2014). Relating working memory to compression parameters in clinically fit hearing aids. *American Journal of Audiology, 23,* 394–401.

Stenfelt, S., & Rönnberg, J. (2009). The signal-cognition interface: Interactions between degraded auditory signals and cognitive processes. *Scandinavian Journal of Psychology, 50,* 385–393.

Stone, M. A., & Moore, B. C. (1992). Syllabic compression: Effective compression ratios for signals modulated at different rates. *British Journal of Audiology, 26,* 351–361.

Stone, M. A., & Moore, B. C. (2004). Side effects of fast-acting dynamic range compression that affect intelligibility in a competing speech task. *The Journal of the Acoustical Society of America, 116,* 2311–2323.

Stone, M. A., & Moore, B. C. (2007). Quantifying the effects of fast-acting compression on the envelope of speech. *The Journal of the Acoustical Society of America, 121,* 1654–1664.

Studebaker, G. A. (1985). A rationalized arcsine transform. *Journal of Speech and Hearing Research, 28,* 455–462.

Tremblay, K. L., Piskosz, M., & Souza, P. (2003). Effects of age and age-related hearing loss on the neural representation of speech cues. *Clinical Neurophysiology, 114,* 1332–1343.

Vaughan, N., Storzbach, D., & Furukawa, I. (2006). Sequencing versus nonsequencing working memory in understanding of rapid speech by older listeners. *Journal of the American Academy of Audiology, 17,* 506–518.

Wiley, T. L., Cruickshanks, K. J., Nondahl, D. M., Tweed, T. S., Klein, R., & Klein, B. E. (1996). Tympanometric measures in older adults. *Journal of the American Academy of Audiology, 7,* 260–268.

Wingfield, A., Tun, P. A., Koh, C. K., & Rosen, M. J. (1999). Regaining lost time: Adult aging and the effect of time restoration on recall of time-compressed speech. *Psychology and Aging, 14,* 380–389.

Zahorik, P. (2009). Perceptually relevant parameters for virtual listening simulation of small room acoustics. *The Journal of the Acoustical Society of America, 126,* 776–791.