# Effects of Reverberation and Compression on Consonant Identification in Individuals with Hearing Impairment

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**Objectives:** Hearing aids are frequently used in reverberant environments; however, relatively little is known about how reverberation affects the processing of signals by modern hearing-aid algorithms. The purpose of this study was to investigate the acoustic and behavioral effects of reverberation and wide-dynamic range compression (WDRC) in hearing aids on consonant identification for individuals with hearing impairment.

**Design:** Twenty-three listeners with mild to moderate sloping sensorineural hearing loss were tested monaurally under varying degrees of reverberation and WDRC conditions. Listeners identified consonants embedded within vowel–consonant–vowel nonsense syllables. Stimuli were processed to simulate a range of realistic reverberation times and WDRC release times using virtual acoustic simulations. In addition, the effects of these processing conditions were acoustically analyzed using a model of envelope distortion to examine the effects on the temporal envelope.

**Results:** Aided consonant identification significantly decreased as reverberation time increased. Consonant identification was also significantly affected by WDRC release time. This relationship was such that individuals tended to perform significantly better with longer release times. There was no significant interaction between reverberation and WDRC. The application of the acoustic model to the processed signal showed a close relationship between trends in the behavioral performance and distortion to the temporal envelope resulting from reverberation and WDRC. The results of the acoustic model demonstrated the same trends found in the behavioral data for both reverberation and WDRC.

**Conclusions:** Reverberation and WDRC release time both affect aided consonant identification for individuals with hearing impairment, and these condition effects are associated with alterations to the temporal envelope. There was no significant interaction between reverberation and WDRC release time.

**Key words:** Reverberation, Temporal envelope, Wide-dynamic range compression.

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## INTRODUCTION

Reverberation is an acoustic phenomenon present in many everyday listening environments. Reverberation occurs when some acoustic energy waves are reflected off of features of an environment (e.g., a wall) and arrive at the ear after energy waves that traveled via direct trajectory. This delay of acoustic energy disrupts speech recognition. This effect is caused through distortion of the speech signal by the smearing of spectral and temporal information (Nábělek 1988; Nábělek et al. 1989; Watkins & Holt 2000; Bidelman & Krishnan 2010). Reverberation is acoustically distinct from other forms of distortion, such as background noise, and causes a unique pattern of perceptual errors (Nábělek 1988; Helfer & Huntley 1991; Hedrick & Younger 2007). Nábělek et al. describe the effects of reverberation as a function of two main components: self- and overlap-masking. Self-masking refers to the distortion occurring within each phoneme by reverberation. Overlap masking refers to the distortion that occurs when acoustic information from previous phonemes spills over into the subsequent speech components. Both self- and overlap-masking combine to distort the spectral and temporal cues important for speech perception.

Individuals with sensorineural hearing loss are more susceptible than individuals with normal hearing to the adverse effects of reverberation on speech recognition (Duquesnoy & Plomp 1980; Humes & Christopherson 1991; Gordon-Salant & Fitzgibbons 1993, 1995; Halling & Humes 2000; Marrone et al. 2008). In one study by Gordon-Salant and Fitzgibbons (1999), speech recognition performance for elderly individuals with hearing impairment significantly decreased when presented at a relatively minimal reverberation time of 0.4 sec. Reverberation times in real rooms vary widely from nearly zero up to several seconds based on room size and absorptive properties of the room surfaces and materials. For example, a living room with carpets, curtains, and other absorptive materials has a typical reverberation time of 0.50 sec; whereas, a bathroom with hard tiles which reflect much of the acoustic energy may have a reverberation time as high as 2.0 sec. Given the increased susceptibility of individuals with hearing impairment to the effects of even minimal amounts of reverberation, speech perception in reverberation is an important clinical concern when dealing with this population.

For individuals with hearing impairment, hearing aids are the most widely distributed rehabilitation device. While hearing aids have been shown to improve individuals' speech recognition in reverberant environments (Nábělek & Pickett 1974; Hawkins & Yacullo 1984; Johnson et al. 2010), hearing aid users nonetheless report significant dissatisfaction with their device's performance in reverberant environments (Kochkin 2010). The effects of reverberation on hearing aid processing have been explored for a few hearing aid features, including adaptive directional microphone technology either in isolation or combined with digital noise reduction (Hawkins & Yacullo 1984; Ricketts 2000; Walden et al. 2000; Ricketts & Henry 2002). However, there is still a relative paucity of information on the effects of reverberation on hearing aid processing as compared with other forms of environmental distortion, such as noise.

Of particular interest in the present study is the core processing strategy in all digital hearing aids: wide-dynamic range compression (WDRC). A WDRC amplifier applies differential

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amounts of gain based on the level of input, such that low-intensity inputs will receive more gain than high-intensity inputs. The speed at which the processor reacts to changes in input level depends on the attack time (AT) and release time (RT).

In consumer hearing aids, AT values are typically short to activate rapid decreases in gain following loud impulse noises (e.g., a door slamming); however, RT values range from very short (e.g., ~20ms) to very long (e.g., several seconds). Shorter RTs provide improved audibility to speech by quickly returning gain to low-intensity phonemes directly after higher-intensity speech components; however, these short RTs have also been shown to distort the temporal characteristics of the signal which provide important linguistic information for speech recognition (Plomp 1988; Rosen 1992). Because of the complicated relationship between these factors, there is no clear consensus on how WDRC RTs should be set. Some studies have suggested that longer RTs may be better for intelligibility and sound quality (Neuman et al. 1998; Hansen 2002; Moore et al. 2004); whereas other studies have suggested that shorter RTs may provide better consonant audibility (van Toor & Verschuure 2002; Jenstad & Souza 2005). The contrasting findings of these studies demonstrate the variable nature of optimal RT settings.

One reason for this inconsistency is that optimal hearing aid processing often varies situationally (e.g., Nábělek 1983). Most of the research investigating the effects of hearing aid amplification strategy on reverberant speech was published before WDRC was the preeminent hearing aid amplification algorithm, and so it is mostly outdated. Only two articles have explicitly investigated the interaction between compression speed and reverberation on speech intelligibility.

Nábělek (1983) investigated the effects of different amplitude compression strategies on reverberant speech. In that study, 10 participants identified nonsense syllables under linear amplification and three-channel multiband compression conditions with an AT of 1 msec and a RT of 20 msec. When individuals with hearing impairment listened to speech in a reverberant environment (reverberation time = 0.8 sec) using linear and WDRC amplification, there was no difference in speech recognition for either amplification strategy. This suggests that there is no benefit of WDRC. However, that study investigated a very limited range of reverberation and WDRC conditions.

Shi and Doherty (2008) expanded these findings by including more WDRC and reverberation conditions in the research design. The authors tested sentence intelligibility in 30 individuals with wearable hearing aids set with either a long RT (1500 msec) or short RT (90 msec) at reverberation times up to 3.6 sec. Results here indicated that increasing amounts of reverberation significantly decreased sentence intelligibility. The authors also found that WDRC amplification with both long and short RTs resulted in improved speech intelligibility over linear amplification; however, there was no significant difference observed between fast and slow compression. This suggests that RT does not have an effect on reverberant speech perception. This is a puzzling result, considering the expected consequences of WDRC RT on temporal envelope fidelity and subsequent behavioral effects (Verschuure et al. 1994; Kates 2010); however, the previous study did not perform any acoustic analysis to examine the physical alterations occurring to the signal as a result of reverberation or WDRC.

Thus, these studies yielded discrepant results. Nábělek (1983) concluded that there was no effect of WDRC versus linear amplification on reverberant speech intelligibility; Shi and Doherty (2008) concluded that there was an overall effect of WDRC, but there was no effect of RT on reverberant speech intelligibility. These studies were limited in their investigation of the range of reverberation and WDRC RT conditions implemented. Shi and Doherty (2008) investigated the effects of WDRC RT as a dichotomous variable of fast- versus slow-acting WDRC. However, in real hearing aids, RT values vary widely along a continuum. In addition, neither study investigated the acoustic effects of reverberation and WDRC on the signal. This limits the conclusions that can be drawn from the behavioral results, since it is impossible to assess what acoustic effects (if any) the signal processing manipulations had on the signal.

The purpose of the present study was to further explore the relationship between reverberation and WDRC processing. This project addressed this goal in two primary ways: (1) By investigating reverberation and WDRC across a wide range of externally valid conditions. This was achieved through reverberation and WDRC simulations that allowed for controlled and systematic implementation of variable values and contrasts. (2) By applying an acoustic model of temporal envelope alteration to the processed stimuli. The application of an acoustic model allowed for further investigation of the acoustic effects of reverberation and WDRC and how these acoustic alterations are associated with behavioral results.

## MATERIALS AND METHODS

### Participants

Participants included 23 adults (mean = 76.2 years, range 57 to 90 years; 13 males) with mild to moderate sloping, symmetrical, sensorineural hearing loss. All individuals were recruited from the greater Chicago area. Participants were evaluated using a standard audiometric protocol including case history, otoscopy, pure tone audiometry, and tympanometry. Participants were included based on results of pure tone audiometry: air conduction testing was performed at 0.25 to 8 kHz octave frequencies, and interoctaves at 3 and 6 kHz; bone conduction was performed at octave frequencies 0.5 to 4 kHz. Participants with conductive loss (defined as two air-bone gaps greater than 10 dB at any two frequencies and/or irregular tympanometry re: American Speech-Language-Hearing Association 1997) were excluded from the study. All participants reported good general health at the time of testing and no history of neurologic or otologic impairment. Participants all spoke English as their sole or primary language. Individuals completed an informed consent process and were compensated for their time. Participant audiograms for their test ear, and the group mean can be seen in Figure 1. The test ear was always the individual's better ear or their right ear in cases of complete symmetry.

### Stimuli

Test stimuli were a set of 16 vowel–consonant–vowel (VCV) syllables consisting of different consonants /b, d, g, p, t, k, f, θ, v, ʒ, ʃ, ð, z, s, m, n/ spoken in an /aCa/ context (Turner et al. 1995). VCV stimuli were selected to limit the role of cognitive processes in the task. VCV stimuli were additionally selected to investigate the effects of reverberation and WDRC at a phonemic level. Each syllable was produced by 4 talkers (2 females,

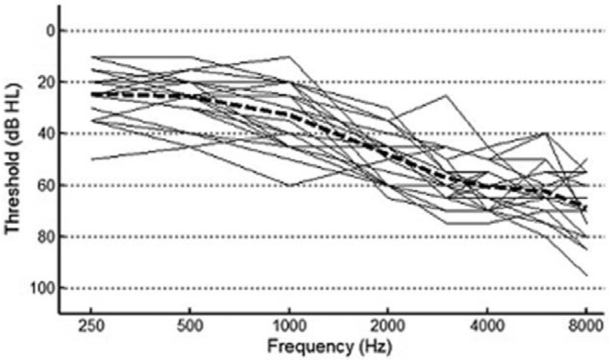

Fig. 1. Individual participant audiograms for their test ear; group mean thresholds in *dotted black line*.

2 males) to avoid individual idiosyncrasies. This results in 64 total VCV stimuli. All participants were instructed on /z/ vs /ʒ/ and /θ/ vs. /ð/ distinctions before testing. The entire set of stimuli was then processed in two stages: reverberation and WDRC simulations.

## Processing

- Stage 1: Reverberation Simulator

Binaural room impulse responses for different reverberation times were calculated using virtual acoustic techniques (Zahorik 2009). Different reverberation times were obtained by changing the absorptive properties of the reflective surfaces while the size of the virtual room and the position of the source and listener were kept constant. The VCV stimuli tokens were convolved with the binaural room impulse responses to get the reverberant signals. Simulated room size and source-listener distance are specified in Table 1.

The simulation method used an image model to compute directions, delays, and attenuations of the early reflections, which were spatially rendered along the direct-path using non-individualized head-related transfer functions (Allen & Berkley 1979). The late reverberant energy was simulated statistically using exponentially decaying Gaussian noise. Further details of the reverberation simulator can be reviewed in Zahorik (2009). Overall, this method of room simulation has been found to produce reverberation simulations that are reasonable physical and perceptual approximation of those measured in real rooms (Zahorik 2009).

The range of reverberation times selected (0.0, 0.50, 1.0, 2.0, and 4.0 sec) was selected to reflect the range of real world reverberation times. The 0.0 sec reverberation time denotes an anechoic signal: signal with just the direct path and no reflections. The relatively mild reverberation times of 0.50 and 1.0 sec reflect listening in average rooms in a house; whereas, the higher reverberation times of 2.0 and 4.0 sec are closer approximations of listening in highly reverberant environments, such as bathrooms, places of worship, or theaters (Bradley 1986). Processing of the 64 VCV tokens resulted in 320 unique stimuli (16 consonants × 4 talkers × 5 reverberation times), which were then subjected to the WDRC simulator.

**TABLE 1. Parameters of the reverberation simulator used to process the reverberation stimuli**

| Reverberation Simulation Parameters | |
|---|---|
| Room volume | 5.7 m × 4.3 m × 2.6 m |
| Source-listener distance | 1.4 m |
| Reverberation times | 0.0, 0.50, 1.0, 2.0, 4.0 sec |

- Stage 2: WDRC Simulator

The stimuli were next processed through a virtual hearing aid compression circuit to provide a range of envelope alteration. This program can be modified to simulate any combination of compression characteristics, such as threshold kneepoint, compression ratio, and attack and RTs or number of compression channels. In brief, the simulator processes the signal into a six-channel filter bank followed by a peak detector that reacts to increases in the within-band signal level with the AT and decreases in the signal level with the RT. Stimuli were individually processed through the simulator without a carrier phrase. Further details of the WDRC simulator can be reviewed in Arehart et al. (2010). All parameters except for RT were held constant to isolate the effects of RT. These parameters were set to common values representative of most WDRC processing in consumer hearing aids. Processing parameters for the WDRC stage of processing can be seen in Table 2. The RT conditions selected (12, 90, 800, and 1500 msec) reflect a range of WDRC RTs used in real hearing aid circuits. The input speech level was 65 dB SPL to represent a conversational speech level. The set of 320 stimuli after reverberation simulation was then processed at these 4 RT values to yield the final set of 1280 VCV stimuli.

## Behavioral Procedure

Stimulus presentation and scoring were controlled by a local Matlab program. Test protocol for each participant included a 320 stimuli subset of the total stimuli set. These stimuli were counterbalanced such that each of the four unique talkers was equally represented across the consonants, RTs, and reverberation times (16 consonants × 5 reverberation times × 4 RTs). Stimuli were blocked by the four RTs and reverberant stimuli were randomized within each block to prevent acclimatization to the reverberant characteristics of the listening environment (e.g., Brandewie & Zahorik 2010; Srinivasan & Zahorik 2013). The order of the four blocks was counterbalanced across subjects. After each trial, participants indicated the consonant perceived in a 16 alternative forced choice task using a computer mouse to navigate a screen display. Listeners did not receive feedback during testing. Total testing time took 2 hr including audiometric protocol and consent. During testing, breaks were provided at 20-min intervals to prevent fatigue.

Signals were presented monaurally in the listener's better ear at 68 dB SPL to represent conversational level and account for

**TABLE 2. Parameters of the WDRC simulator used to process the final stimuli set**

| Compressor Simulation Parameters | |
|---|---|
| Compression threshold | 45 dB SPL |
| Compression ratio | 3:1 |
| Attack time | 10 msec |
| # Channels | 6 |
| Release times | 12, 90, 800, 1500 msec |

*WDRC, wide-dynamic range compression.*

loss of binaural summation. Listeners received individual NAL-NL1 shaping to provide sufficient audibility (Byrne & Dillon 1986). Shaping was based on a single input level so as not to influence the effect of WDRC differentially across listeners with different audiometric losses. One-third octave band levels for the final output signal were measured in a 2-cc coupler and compared with the desired NAL-NL1 target values specified in the same 2-cc coupler using a sound level meter. Consistent with clinical practice, measured output was within ±5 dB of target at all third octave bands through 8000 Hz. The digital signals were converted to analog using Tucker-Davis Technologies equipment (RX6, Alachusa, FL) and played through Etymotic ER-2 insert earphones (Elk Grove Village, IL). All procedures were approved by the Northwestern University Institutional Review Board.

### Acoustic Analysis

Stimuli were acoustically analyzed using the envelope difference index (EDI; Fortune et al. 1994). The EDI quantifies temporal envelope alteration between two acoustic signals and was calculated using locally developed Matlab code. Two signal comparisons were made: (1) Modeling the effects of reverberation by comparing the signal envelopes of the anechoic syllable with the reverberant version of the same syllable. In this instance, anechoic digital files were zero padded to be the same length as the reverberant file. This comparison examines the effects of reverberation on temporal envelope. (2) Modeling the effects of WDRC by comparing the signal envelopes of the reverberant uncompressed syllable with the reverberant compressed version of the same syllable. This second comparison examines the effects of WDRC on the temporal envelope.

In both of these comparisons, first a syllable was rectified and digitally low-pass filtered using a Butterworth sixth-order filter with a 50-Hz cutoff to obtain the syllable envelope. The envelope was downsampled to a sampling frequency of 6000 Hz, and the mean amplitude of the syllable was calculated. Each sampled data point of the envelope was scaled to the mean amplitude by dividing every value by the mean. This provided a common reference for comparing the two envelopes. These same steps were performed on the second syllable. The EDI was calculated using the equation below:

$$\mathrm{EDI}=\left(\sum_{n=1}^{N}\left|\mathrm{Env1}_n-\mathrm{Env2}_n\right|\right)/\,2N,$$

where $N$ = number of sample points in the waveforms, $\mathrm{Env1}_n$ was the reference signal (either anechoic or reverberant uncompressed depending on the comparison). $\mathrm{Env2}_n$ was the comparison signal (either the reverberant or reverberant compressed signal corresponding to the appropriate comparison condition):

## RESULTS

### Behavioral Results

Data were analyzed using a two-way repeated measures analysis of variance (RM-ANOVA) with two independent factors (reverberation time and RT) to assess whether there were differences in consonant identification. To stabilize the variance of the dependent variable, absolute scores were transformed to rationalized arcsine units (Studebaker 1985). There was a significant main effect of reverberation time [$F(4,19) = 73.656$, $p < 0.001$], with large effect size partial $\eta^2 = 0.939$. There was also a significant main effect of RT [$F(3,20) = 16.268$, $p < 0.001$]. The effect of RT was smaller than that of reverberation with a partial $\eta^2 = 0.709$. The RT × reverberation time interaction was not significant [$F(12,11) = 1.239$, $p = 0.365$]. Before data collection, an a priori power analysis was conducted using G*Power software to determine that a sample size of 24 would be necessary to provide a power of 0.80 for a medium effect of the interaction with an $\alpha = 0.05$ criterion for significance. While the current sample falls one subject short of the recommended value for 0.80 power, given the current $p$ value of this test it is highly unlikely that an additional subject would lead to a significant result. The data for reverberation time and RT are plotted in Figure 2.

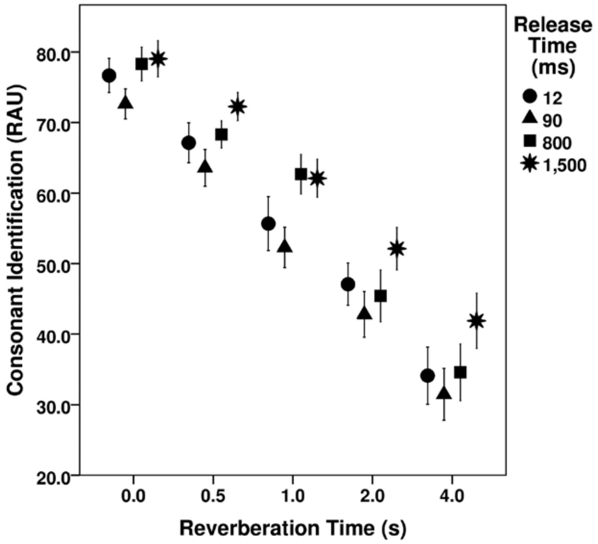

Fig. 2. Consonant identification scores in RAUs of reverberant VCV stimuli at five different reverberation times for four different release time processing conditions. The error bars represent ±1 standard error. RAU, rationalized arcsine unit; VCV, vowel–consonant–vowel.

To further explore the main effects found in the RM-ANOVA, pairwise comparisons were made with significance level controlled via a Bonferroni correction. Pairwise comparisons showed that consonant identification scores were significantly higher for the 1500 msec RT setting over the 12 msec ($p = 0.005$), 90 msec ($p < 0.001$), and 800 msec ($p = 0.045$). Scores were significantly higher for the 800 msec RT setting over the 90 msec RT setting ($p = 0.006$). There were no significant differences between the 12 and 800 msec RTs ($p = 1.0$) and 12 and 90 msec RTs ($p = 0.185$). Increasing the reverberation time significantly decreased consonant identification scores for all pairwise comparisons ($p < 0.001$).

In addition, there was evidence for individual variability in sensitivity to reverberation. The RM-ANOVA resulted in a significant interaction between individual listener and reverberation time ($p < 0.001$). Listeners ranged from approximately 20% loss of recognition in reverberation to upwards of 70% loss of recognition in reverberation when compared with individual baseline scores. This suggests that some individuals are more susceptible to increasing amounts of reverberation and exhibit a greater decrease in performance with increasing reverberation.

To further examine this source of individual variability, a multiple regression was conducted to determine if listener age

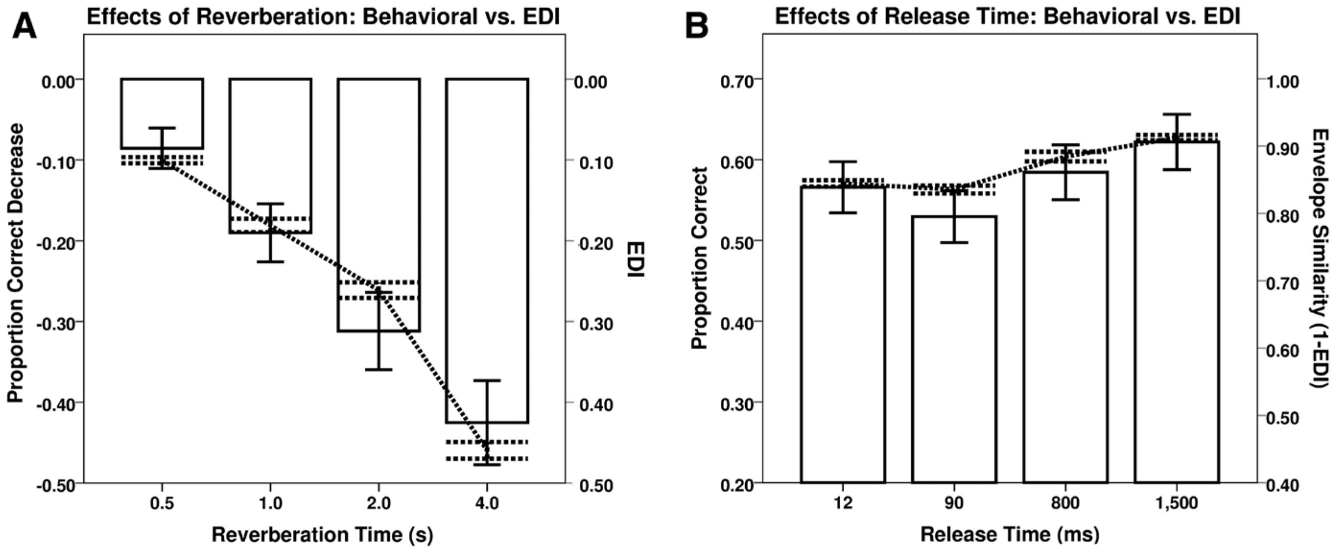

Fig. 3. Comparison of acoustic results of the EDI with behavioral results. The bars depict behavioral performance as a function of reverberation time (A) and release time (B). Behavioral performance scale for each graph is on left axis. The *dotted lines* depict EDI results. Acoustic result scale for each graph is on right axis. Error bars for both graphs and for the bars and lines represent ±1 standard error. EDI, envelope difference index.

and degree of hearing loss predicted the consonant identification performance in the most reverberant condition. Degree of hearing loss was quantified by three-frequency pure-tone average (500, 1000, and 2000 Hz), and a composite score for the 4 sec reverberation time condition was calculated by taking the arithmetic mean of performance across the four RTs. Results of this analysis can be seen in Table 3. These two listener factors combined explain 60.2% of the variance in listener performance [$F(2,20) = 15.123$, $p < 0.001$, $R^2 = 0.602$]. The model shows that listener age was a significant predictor [beta = −0.623, $t(20) = -3.966$, $p = 0.001$]; however, pure-tone average did not significantly predict performance [beta = −0.263, $t(20) = 0.109$].

### Acoustic Results

Because there was no interaction in the behavioral data, results of the EDI were analyzed separately for reverberation and WDRC using one-way ANOVAs. Within each one-way ANOVA, results were collapsed across the variable not being investigated. There was a significant main effect of amount of reverberation on changes to the temporal envelope as measured by the EDI [$F(3,60) = 334.459$, $p < 0.001$]. Posthoc tests were conducted using a Bonferroni correction for multiple comparisons. All pairwise comparisons were significantly different ($p < 0.001$). These results match the trend in the behavioral data in which participants demonstrated significantly poorer consonant identification with increasing reverberation times. The similar trends of the behavioral and acoustic results can be seen in Figure 3. The behavioral results are scaled relative to performance in the anechoic condition; the EDI results are depicting the amount of change occurring to the syllables caused by reverberation.

**TABLE 3. Model explaining consonant identification performance in reverberation by patient characteristics (age and pure-tone average)**

| Variable | Beta | *p* |
|---|---|---|
| Age | −0.623 | 0.001 |
| Pure-tone average | −0.263 | 0.109 |
| Model $R^2 = 0.602$ | | |

EDI values for RT were similarly analyzed using a one-way ANOVA. The EDI values were obtained comparing individual consonants under the reverberant condition with the same consonant and reverberation condition after compression. The values were then transformed to represent the similarity between the reverberant and reverberant + compressed signals (i.e., 1-EDI). Thus in this comparison, higher numbers mean less distortion occurring as a result of WDRC. There was a significant main effect of WDRC RT on changes to the temporal envelope as measured by the EDI [$F(3,316) = 41.762$, $p < 0.001$]. Posthoc tests were conducted using a Bonferroni correction for multiple comparisons. Results of the posthoc tests matched that of the behavioral experiment. There was no significant difference between the 12 and 90 msec conditions ($p = 1.0$). The 1500 msec RT caused significantly less distortion compared with the 800 msec ($p = 0.002$), 90, and 12 msec RTs ($p < 0.001$), and the 800 msec RT caused significantly less distortion than the 90 and 12 msec RTs ($p < 0.001$). The similar trends of the behavioral and acoustic results can be seen in Figure 3. The behavioral results are plotted as raw proportion correct for each RT condition. The EDI results are depicting the amount of change occurring to the syllables caused by different WDRC RTs. The EDI results are scaled relative to behavioral performance in the 12 msec RT condition.

## DISCUSSION

The present study evaluated the effects of reverberation and RT on consonant recognition in individuals with hearing impairment. Effects were assessed using behavioral testing and via the application of the acoustic EDI model, which evaluates the amount of temporal distortion occurring to a signal. Consonant identification was significantly reduced as the amount of reverberation increased. There was also a significant main effect of WDRC RT on performance. This relationship was such that participants achieved the highest intelligibility with longer RTs. There was no significant interaction between reverberation and WDRC, and both manipulations had additive effects. Trends of the EDI were consistent with behavioral results: both reverberation and WDRC cause significant changes to the temporal envelope as measured by the acoustic model. These parallel trends of behavioral and acoustic results suggest that behavioral performance is associated with changes to the temporal envelope.

## Reverberation

The findings of the present study are consistent with previous results suggesting that individuals with hearing impairment are significantly affected by even mild amounts of reverberation (e.g., Helfer & Wilber 1990; Humes & Christopherson 1991; Gordon-Salant & Fitzgibbons 1993, 1995, 1999; Sato et al. 2007; Shi & Doherty 2008). This vulnerability of individuals with hearing impairment to reverberation has important implications for testing. Much of the research in speech perception of individuals with hearing impairment involves anechoic presentation of sounds to the listener; however, this is not indicative of many realistic listening conditions in which some base level amount of reverberation would be present. While the normal auditory system is able to cope with these mild reverberation (e.g., Humes & Christopherson 1991; Gordon-Salant & Fitzgibbons 1993, 1999), as demonstrated here, listeners with hearing impairment are significantly affected. In addition, most clinical fittings and validations are performed under idealized conditions which contain very little reverberation. These environments may not represent the different listening environments in which hearing aid users will primarily be listening through their device. Thus, it might be important to provide validation for supplemental testing of performance of hearing aid users in more realistic adverse conditions than is currently applied for functional testing. This suggests that testing, both clinical and research, should incorporate some reverberation into speech perception measures to better approximate real-world listening and improve external validity.

Declines in intelligibility as a function of reverberation from the behavioral task were paralleled by distortion to the temporal envelope as measured by the EDI. Reverberation is a multi-faceted source of distortion that affects both the spectral and temporal properties of speech (Nábělek 1988; Nábělek et al. 1989; Watkins & Holt 2000). While the EDI only captures acoustic effects to the temporal envelope and does not include spectral or fast-modulation distortion, the results of the EDI still successfully modeled the behavioral effects. The EDI has not previously been used in the literature to quantify the distortive effects of reverberation. This suggests that the EDI can successfully be used clinically to model how reverberation will affect intelligibility for listeners with hearing impairment.

Interestingly, not all individuals were equally affected by reverberation; some participants were significantly more susceptible to the deleterious effects of reverberation on speech recognition. Results of this study suggest that age is a significant factor driving susceptibility to reverberation, whereas degree of hearing loss is not. This is consistent with previous studies that have identified a significant effect of age on reverberant speech intelligibility (Plomp & Duquesnoy 1980; Gordon-Salant & Fitzgibbons 1993, 1995). Previous studies have also suggested that performance in reverberation may be affected by individual factors including temporal resolution (Gordon-Salant & Fitzgibbons 1995, 1999), degree of hearing loss (Gordon-Salant & Fitzgibbons 1993; Marrone et al. 2008), and cognition (Kjellberg 2004). If any of these measures are sufficiently sensitive and specific for indicating reverberant susceptibility, such a measure could be used clinically to identify patients who would benefit most from hearing aid algorithms focused on improving reverberant speech. These patients could then be fitted with reverberation suppressing signal processing features in the initial fit to proactively address this individual deficit. However, further research is necessary to understand the underlying traits driving susceptibility to reverberation and the efficacy of these signal processing features.

## WDRC

In the present study, the WDRC RT significantly affected consonant identification even in the presence of reverberation. Thus, the parameters involved in WDRC processing did have an effect on speech perception even under reverberant conditions. This finding is in contrast with the previous study investigating the effects of WDRC RT on reverberant speech (Shi & Doherty 2008). In the previous study, listeners performed significantly better with fast and slow compression over a linear system; however, there was no difference in speech intelligibility between the fast and slow compression systems. These differing results could be due to several methodological differences between the studies. The present study used a fixed compression ratio of 3:1, whereas Shi and Doherty (2008) used individualized compression ratios for each listener based on NAL-NL1 standards resulting in compression ratios between 1.07 and 2.67. It has been demonstrated that higher compression ratios exacerbate the effects of RT (Neuman et al. 1998; Olsen et al. 2004). The fixed 3:1 compression ratio used in this study represents the upper limit of the range typically used in WDRC hearing aids. While real hearing aids provide individualized compression ratios based on audiometric configuration, the uniform application of compression provided the same degree of envelope alteration to ensure that identical stimuli were presented to all listeners. This also allowed for the use of the EDI model to examine the acoustic effects of WDRC RT since each participation received the same amount of compression.

Another possibility for this discrepancy is due to the differences in the stimulus type used between the two studies to assess speech intelligibility. Shi and Doherty (2008) used the speech in noise test. In this test, intelligibility is scored on the basis of whether individuals are able to identify the last word of a sentence. The present study used isolated nonsense syllables in which the task is to identify the consonant embedded between two vowels. Because reverberation has a greater effect on speech recognition than WDRC, it could be that the effect of reverberation overpowers the smaller effects of WDRC by the final word of the sentence. In other words, in a sentence there would be more overlap masking because there are more preceding phonemes compared with a single vowel. It was suggested by Shi and Doherty that reverberation may do this by "masking" the smaller effects of RT. However, this is unlikely because the present study used a higher reverberation time that would cause a greater amount of distortion than Shi and Doherty, and the effect of RT remained even in the presence of this more extreme condition. In addition, results of the EDI comparison demonstrated that RT significantly affects the temporal envelope even in the presence of reverberation. Thus, there are additive effects of RT on consonant recognition associated with changes to the temporal envelope that persist even under highly reverberant conditions.

Another possibility for this difference is that nonsense syllables are more sensitive stimuli to the effects of RT. Participants in Shi and Doherty (2008) were listening to sentences and had access to some context information and a longer speech stimulus to identify. However, the present study used nonsense syllables in which the task was to identify a low-intensity consonant embedded between two high-intensity vowels. In this instance, the preceding vowel triggered the compression of the hearing aid simulator. The short RT (12 msec) is sufficiently fast to restore gain to the consonant portion; whereas, the longer RTs did not allow the hearing aid simulator to fully restore gain in time to amplify the consonant. Thus, the effect of varying RT would be greatest for the consonant portion, and it may be that with a longer utterance this effect would be minimized.

This study is consistent with several other studies (for nonreverberant speech) that have demonstrated that fast compression results in worse performance when combined with high compression ratios (Verschuure et al. 1994; Stone & Moore 2004, 2008). The effects of RT in the present study were related to distortion to the temporal envelope, and significant changes to the temporal envelope resulting from WDRC corresponded to significant changes in the behavioral results. These findings are consistent with the idea that individuals even with mild degrees of hearing loss depend to varying extents on the temporal cues of speech (Souza et al. 2015), and this relationship between envelope distortion and speech recognition is consistent with previous applications of the EDI for nonsense syllables; however, it has been noted that WDRC does not affect all consonants equally (Jenstad and Souza 2005, 2007). Jenstad and Souza observed that voiceless consonants were more affected by WDRC. The present study did not have sufficient consonant repetition within each processing condition to analyze specific error patterns. However, presumably because there was no overall interaction between reverberation and RT for consonant recognition, these error patterns would be similar under reverberant conditions.

Given the increased susceptibility of hearing-impaired individuals to reverberation, it is unsurprising that hearing aid users report significant relative dissatisfaction in reverberant environments (Kochkin 2010). Algorithms have been specifically proposed to address the issue of environmental reverberation in hearing aid amplification (e.g., Lebart et al. 2001; Kusumoto et al. 2005; Wu & Wang 2006). Currently, some hearing aid manufacturers offer features designed to suppress the effects of reverberation. These features work primarily through adjusting the time constants of the compressor. This study suggests that altering the WDRC constants can have acoustic and behavioral effects on listener speech intelligibility in reverberant environments.

## General Discussion

The use of the EDI in the present study was able to model both the effects of reverberation and WDRC on the signal acoustics. The EDI results paralleled the behavioral results of the consonant identification task. This conclusion is consistent with previous studies using the EDI to model distortion effects (e.g., Jenstad & Souza 2005, 2007; Souza et al. 2012). This study further demonstrates the validity of the EDI's usefulness as a means of modeling distortion occurring to the temporal envelope resulting from external factors (e.g., reverberation and noise) and factors related to the hearing aid signal processing (e.g., WDRC settings). This study expands the potential clinical use of the EDI by presenting evidence that the EDI can be used to model the effects of reverberation. Moreover, the EDI can be used to examine the effects of the acoustic environment and hearing aid processing simultaneously to predict performance.

While these effects were observed in the present study under monaural laboratory conditions, it is not certain whether these effects will generalize to real-world reverberant environments with actual hearing aids. Clinical hearing aids provide compression characteristics individualized for each listener based on residual dynamic range. This would likely lead to smaller compression ratios than that used in the present study.

Another consideration is the role of compression and audibility. A primary goal of fast-acting WDRC is to provide customized gain suited to each syllable or phoneme to place the greatest amount of speech energy within the listener's dynamic range. In the present study, speech tokens were processed through the WDRC simulator at 65 dB SPL input. This represents a conversational speech level which would have provided good audibility for the mild to moderate degrees of hearing loss, regardless of compression speed. Thus, having shorter RTs may have had minimal effects on audibility which would not outweigh the detrimental effects of distorting the temporal characteristics of speech. It would be of further interest to examine how varying speech level would affect this relationship between reverberant speech and WDRC RT.

The results of this experiment suggest that hearing aid processing has an additive effect to reverberation that manifests itself both acoustically and behaviorally. Results also suggest that the EDI can be used to simultaneously model the acoustic effects of reverberation and WDRC processing. Previous research in the area of WDRC settings and adverse listening conditions has demonstrated a higher order interaction among WDRC, acoustic environment, and individual cognition (Lunner & Sundewall-Thorén 2007; Rudner et al. 2009; Ohlenforst et al. 2014). The present study did not consider individual cognition effects because the nature of the stimuli were unlikely to substantially engage cognitive processes; however, based on this previous research, indicating a relationship among environmental, individual, and signal processing factors, further investigation is warranted in the area of reverberation and signal processing as well as under more realistic conditions (e.g., real hearing aids, background noise which would likely be present in most reverberant environments, etc.). The present study represents a step toward understanding this interaction by investigating these effects at a phonemic level both acoustically and behaviorally. Further research is necessary to fully understand how to optimize hearing aids to support aided speech recognition in reverberation under more realistic conditions.

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