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The Role of Spectral Resolution, Working Memory, and Audibility in Explaining Variance in Susceptibility to Temporal Envelope Distortion

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Abstract

Background—Several studies have shown that hearing thresholds alone cannot adequately predict listeners' success with hearing-aid amplification. Furthermore, previous studies have shown marked differences in listeners' susceptibility to distortions introduced by certain nonlinear amplification parameters.

Purpose—The purpose of this study was to examine the role of spectral resolution, working memory, and audibility in explaining perceptual susceptibility to temporal envelope and other hearing-aid compression-induced distortions for listeners with mild to moderate and moderate to severe hearing loss.

Research Design—A between-subjects repeated-measures design was used to compare speech recognition scores with linear versus compression amplification, for listeners with mild to moderate and moderate to severe hearing loss.

Study Sample—The study included 15 adult listeners with mild to moderate hearing loss and 13 adults with moderate to severe hearing loss.

Data Collection/Analysis—Speech recognition scores were measured for vowel-consonant-vowel syllables processed with linear, moderate compression, and extreme compression amplification. Perceptual susceptibility to compression-induced temporal envelope distortion was defined as the difference in scores between linear and compression amplification. Both overall scores and consonant feature scores (i.e., place, manner, and voicing) were analyzed. Narrowband spectral resolution was measured using individual measures of auditory filter bandwidth at 2000 Hz. Working memory was measured using the reading span test. Signal audibility was quantified using the Aided Audibility Index. Multiple linear regression was used to determine the predictive role of spectral resolution, working memory, and audibility benefit on listeners' susceptibility to compression-induced distortions.

Results—For all listeners, spectral resolution, working memory, and audibility benefit were significant predictors of overall distortion scores. For listeners with *moderate to severe* hearing

loss, spectral resolution and audibility benefit predicted distortion scores for consonant place and manner of articulation features, and audibility benefit predicted distortion scores for consonant voicing features. For listeners with *mild to moderate* hearing loss, the model did not predict distortion scores for overall or consonant feature scores.

Conclusions—The results from this study suggest that when audibility is adequately controlled, measures of spectral resolution may identify the listeners who are most susceptible to compression-induced distortions. Working memory appears to modulate the negative effect of these distortions for listeners with moderate to severe hearing loss.

Keywords

Speech recognition; hearing-aid amplification; cognition; working memory; audibility; spectral resolution; spectral modulation detection; auditory filter bandwidth; compression; temporal envelope distortion

Introduction

For low-level speech, compression amplification improves audibility, and this improvement in audibility also results in an improvement in speech recognition (e.g., Davies-Venn et al, 2007; 2009; Kates, 2010; Kuk, 2000; Souza, 2002). Less information is available regarding the benefits conferred by improved audibility at conversational and higher speech levels (Kates, 2010). In theory, compression amplification should improve speech understanding by providing the same kind of nonlinear gain as the normal-functioning outer hair cells. However, when speech is presented at conversational or higher levels, some listeners appear to be negatively affected by nonlinear amplification (e.g., Davies-Venn et al, 2009; Kam and Wong, 1999). This phenomenon is seen even among individuals with similar amounts of hearing loss, who might be expected to receive similar benefits of improved audibility (e.g., Souza, 2002).

One possible contributor to differences in benefit is that nonlinear amplification settings such as multiple channels, low compression thresholds, high compression ratios, and fast release times improve audibility of speech signals but also introduce distortions such as overshoot that may alter some of the naturally occurring temporal and spectral information. Previous investigators (e.g., Bor et al, 2008) have shown that compression amplification has the greatest distortive effect on spectral cues such as peak-to-trough ratio when multiple channels are used. Multichannel compression theoretically allows fine adjustments in audibility for listeners with varying hearing-loss configurations, but these independent channels have been shown to diminish salient spectral contrast cues. However, even when spectral distortions are minimized by use of only one or two independent compression channels, this form of nonlinear amplification may also distort naturally occurring temporal cues. Slow-varying intensity changes across time convey temporal envelope cues that are important for recognition of specific speech features, particularly consonant manner of articulation and consonant voicing (Rosen, 1992). Such temporal envelope cues are often classified as secondary to spectral speech cues when speech is presented in quiet (Shannon, 2002). Nonetheless, temporal envelope cues are important for speech recognition, especially when spectral details are distorted by either signal processing or reduced frequency

selectivity (e.g., Shannon et al, 1995); for lower-redundancy signals, such as time-compressed (rapid) speech (e.g., Jenstad and Souza, 2007) or for speech in background noise (e.g., Stone and Moore, 2007).

Considering that temporal envelope cues are important for speech recognition, it is possible that the benefit provided by improved audibility does not always override the effect of altering those cues. Higher input levels will be more susceptible to such alterations because a greater proportion of the signal is above the compression threshold (e.g., Jenstad and Souza, 2005). Susceptibility to compression-induced distortions can be quantified as the extent to which speech recognition scores decrease with nonlinear amplification compared with linear amplification for the same signal. At conversational and higher levels, this susceptibility to compression-induced distortion varies among listeners, and hearing thresholds alone do not distinguish between the listeners who are least susceptible from the ones who are most susceptible (e.g., Davies-Venn et al, 2009).

It is relevant for clinical rehabilitation to determine factors that can be used to distinguish between the listeners who will receive the greatest benefit from the listeners who may receive less benefit from compression amplification that maximizes audibility but alters essential spectral and temporal cues. Beyond auditory thresholds, factors such as spectral resolution (e.g., Gatehouse et al, 2003), audibility (e.g., Dubno and Schaefer, 1992), and working memory (e.g., Lunner, 2003) have each been suggested as possible contributing factors. However, we are not aware of any studies that have simultaneously evaluated the relationship among these three factors on listeners with mild to moderate and moderate to severe hearing loss.

Spectral Resolution

In the context of temporal envelope distortion, a listener with broadened auditory filters may not accurately resolve the spectral cues in speech, even if those cues are audible. Such a listener may rely to a greater extent on temporal envelope cues to aid speech recognition. Therefore, one may assume that such a listener is most likely to be affected by any distortions to the temporal envelope of speech.

If we assume that some listeners rely to a greater extent on temporal envelope cues, how much do temporal envelope distortions matter? Souza et al (2012b) evaluated the effect of temporal envelope distortion on consonant features using spectrally degraded vowel-consonant-vowel (vCv) nonsense syllable tokens presented to listeners with normal hearing. They reported that under spectrally degraded conditions, listeners' scores decreased with increases in envelope distortion. Although those data represent an extreme limitation (four channels of spectral information), they provide evidence that distortion of temporal envelope cues can impair performance. Similar concerns have been raised by other investigators such as Walaszek (2008). Such studies suggest that a measure of spectral resolution may help identify listeners with the greatest susceptibility to temporal envelope distortions.

Working Memory

Central processing may also affect amplification benefit. Recent studies have shown that listeners with limitations in peripheral auditory processing (e.g., elevated thresholds or poor

spectral resolution) can compensate for these limitations in adverse listening environments by recruiting a greater network of prefrontal neural activity (Desjardins, 2011; Wong et al, 2009). It is likely that listeners use linguistic knowledge, vocabulary, and semantic context to resolve ambiguous speech cues when they are in challenging listening environments, such as when they are listening to amplitude-compressed speech or speech in noise (Foo et al, 2007; Lunner and Sundewall-Thorén, 2007; Rönnberg et al, 2008; Rudner et al, 2008). Studies relating cognition to speech recognition have focused on working memory. Working memory is defined as the ability to process and store information that has been shown to correlate with tests of executive function such as complex cognition (Bailey et al, 2008). Several studies have shown that working memory is closely related to the degree of benefit that listeners receive from amplification (Gatehouse et al, 2003, 2006; Lunner, 2003; Akeroyd, 2008; Moore, 2008; Rudner et al, 2009). In general, these studies have shown that listeners with high working memory capacity (WMC) perform better with fast compression release time constants, whereas listeners with low WMC perform better with slow compression release time constants (Rudner et al, 2009; Lunner and Sundewall-Thorén, 2007; Souza and Sirow, 2012). Taken together, these studies suggest that when audibility is sufficient, listeners with poor spectral resolution and high cognitive abilities may not show some of the negative effects of distortions caused by certain nonlinear amplification settings. Therefore, our working hypothesis is that WMC may be a significant factor that distinguishes between the listeners who are good candidates for aggressive nonlinear amplification parameters that optimize audibility despite distortions to spectral and temporal envelope cues.

Audibility

In addition to spectral resolution and working memory, signal audibility is another factor that may contribute to the reported variability in amplification benefit among listeners with hearing loss. Some investigators have reported that audibility explains some or most of the variance in speech recognition scores (Dubno and Dirks, 1989; Humes and Roberts, 1990; Crandell, 1991; Humes et al, 1994; Henry et al, 2005; Gilbert et al, 2008). Inclusion of audibility as a factor in the present study was motivated by a previous study by Davies-Venn et al (2009) in which compression amplification benefit was evaluated at low, moderate, and high input levels for listeners with mild to moderate and severe hearing loss. Listeners either showed no improvement in scores or a slight decrease in scores for wide dynamic range compression (WDRC) amplification at moderate and high input levels. Most importantly, there was higher variance in scores with WDRC compared with linear amplification.

This present study expands on Davies-Venn et al (2009) by evaluating participant-specific factors that may explain the variance in susceptibility to distortions introduced by compression amplification. The working hypothesis was that even in conditions of similar audibility benefit, spectral resolution may predict the listeners who are likely to be most affected by temporal envelope distortion, and WMC may modulate the negative effect of this distortion for some listeners. We hypothesized that a regression model that evaluates the predictive role of spectral resolution, working memory, and audibility benefit will predict compression-induced distortion scores, especially for listeners with moderate to severe hearing loss.

Methods

Participants

A total of 28 adult listeners participated in this study. Pure tone air and bone conduction thresholds, loudness discomfort level (LDL) testing, and the Mini-Mental State Examination (MMSE) were administered to determine each participant's candidacy for the study. The MMSE is a cognitive screening test (Folstein et al, 1975) that evaluates orientation, attention, short-term memory, and the ability to follow simple written or verbal instructions. LDLs were measured using speech stimuli and warble tones at octave and interoctave frequencies from 250 to 8000 Hz, using instructions recommended by Hawkins et al (1987). The LDL values were used to ensure that presentation levels of the test stimuli did not exceed each listener's threshold of discomfort. Listeners were recruited from the greater Seattle area and compensated at an hourly rate for their participation. All listeners had sensorineural hearing loss, defined as an air-bone gap no greater than 10 dB HL at octave frequencies from 500 to 4000 Hz and normal tympanograms (Jerger, 1970).

Thirteen of the listeners had moderate to severe hearing loss, defined as an average of thresholds at 0.5, 1, and 2 kHz or pure-tone average (PTA) between 55 and 85 dB HL. Twelve of the listeners with moderate to severe hearing loss were experienced hearing-aid users (duration of use, 3–36 yr). Eleven of those listeners used WDRC hearing aids, and one listener used a compression-limiting hearing aid. All but one of the aided listeners were aided binaurally. The remaining 15 listeners had mild to moderate hearing loss, defined as a PTA between 25 and 50 dB HL. Four of the listeners with mild to moderate hearing loss were experienced hearing-aid users (duration of use, 3–11 yr). One of those listeners used WDRC and three used compression-limiting amplification. All but one of the listeners with hearing aids were aided binaurally. The mean audio-grams are shown in Table 1. All test procedures were approved by the institutional review board at the University of Washington.

Speech Recognition

Stimuli—The test stimuli were a subset of 16 vCv syllables consisting of voiced and voiceless stops and fricatives and the vowel /a/. The 16 consonants used were orthographically displayed on a touchscreen as follows: aBa, aDa, aGa, aPa, aTa, aKa, aFa, aVa, aTha, aSa, aSha, aCha, aZHa, aNa, and aMa. Each token was produced by two male and two female talkers for a total of 64 unique syllables, digitally recorded with a 44.1 kHz sampling rate. All test stimuli were presented at 70 dB SPL plus individualized National Acoustic Laboratories (NAL) prescribed gain (Byrne and Dillon, 1986). The individual NAL-prescribed gain for each octave frequency from 250 to 6000 Hz was applied to the test signal via a locally developed MATLAB (MathWorks) computer algorithm. Although no output limiting was used, presentation levels did not exceed any participant's LDLs and no participant reported discomfort from any stimulus presentation level. The speech stimuli were presented at overall sound pressure levels of 88.1, 87.1, and 85.5 dB SPL for listeners with mild to moderate hearing loss and 93.1, 92.5, and 92.5 dB SPL for listeners with moderate to severe loss, for the linear, moderate compression, and extreme compression conditions, respectively.

Amplitude Compression—Amplitude compression reduces the intensity difference between soft and loud sounds (e.g., consonants and vowels). This reduction in the intensity difference has been shown to distort the naturally defined gross temporal envelope shape of speech (e.g., Jenstad and Souza, 2005). All test stimuli were processed with three different signal processing conditions: linear, moderate compression, and extreme compression. The stimuli in the linear condition were processed by applying NAL gain to each vCv syllable via a locally developed MATLAB program. The moderate and extreme compression conditions were amplitude compressed before frequency-gain shaping using a simulation program (Gennum i/o v 1.0). The compression parameters used were as follows: an attack time of 6 msec, a release time of 12 msec, and a compression threshold of 40 dB SPL. The compression ratios were 4:1 for the moderate and 10:1 for the extreme compression settings. Because the experimental question was focused on response to envelope alteration, no attempt was made to constrain the compression parameters to those used clinically. Rather, the compression parameters used in the current study were chosen to yield a predetermined range of amplitude envelope distortion indices (EDIs).

The EDI is an index that quantifies change in the temporal envelope of a test signal compared with a reference signal. It was introduced by Fortune et al (1994) and adapted by Jenstad and Souza (2005) for assessing the effect of hearing aid distortion on listeners with hearing loss. In Equation 1, it is mathematically described as:

$$EDI = \sum_{n=1}^N \frac{|Env1n - Env2n|}{2N}, \quad (1)$$

where N = number of sample points in the waveforms, $Env1n$ = the envelope of the reference signal's waveform, (i.e., an uncompressed syllable token), and $Env2n$ = the envelope of the test signal's waveform (i.e., an amplitude-compressed syllable token). The envelope of the reference and test signal waveforms were first full-wave rectified and low-pass filtered using a 50 Hz cutoff value. Next, the mean amplitude of the signal was computed and the envelope was scaled to the mean amplitude by dividing each sampled data point by the mean. The EDI is a proportion, such that an EDI value of 0 implies no difference in the temporal envelope of the two signal waveforms, whereas an EDI value of 1 implies complete difference in the temporal envelope of the two waveforms. For example, a very large EDI (i.e., approximately 1.0) could imply complete flattening of the temporal envelope of a speech signal.

The EDI values were chosen based on reports from previous studies that suggested EDI values between 0.2 and 0.4 for sentences and between 0.11 and 0.18 for spectrally degraded vCv syllables may result in reduced speech recognition (Jenstad and Souza, 2005, 2007; Souza et al, 2012c). To this effect, the nonsense syllable tokens used in the current study were systematically processed to create compression-induced amplitude envelope distortion (i.e., flattening). The mean EDI values were 0.16 in the moderate compression condition and 0.21 in the extreme compression condition. An illustration of the amplitude envelope change and EDI values for the syllable token “azha” for the moderate and extreme compression conditions as well as clinical compression conditions is shown in Figure 1.

Procedure

A within-subject repeated-measures design was used to evaluate consonant recognition for both listener groups. All test stimuli were presented using Sennheiser 280 Pro earphones, and listeners were seated in a sound-isolating booth. Participants were trained to select the stimulus heard from a touchscreen display of orthographically represented (e.g., “aKa,” “aFa”) vCv syllables. Correct-answer visual feedback was used during practice blocks. Each participant completed 2 practice blocks followed by 12 test blocks (4 blocks for each of the three amplification conditions). Syllables were blocked by amplification condition (i.e., linear, moderate compression, and extreme compression, in random order). The presentation order of the syllables was also randomized within each block. For each practice block, 256 randomly ordered trials (4 repetitions of each of the 64 syllables) were presented at 70 dB SPL using linear amplification. Absolute scores were computed by averaging listeners' scores from four blocks in each of the three test conditions.

Audibility

Amplified signal audibility was quantified using the Aided Audibility Index (AAI). The AAI indicates how much of an amplified speech signal falls above a listener's threshold (Stelmachowicz et al, 1994). To compute the AAI, listeners' pure-tone thresholds were converted from dB HL to dB SPL thresholds centered at third-octave frequencies from 160 to 8000 Hz using the formula by Pittman and Stelmachowicz (2000). To determine the speech input level, a concatenated version of each listener's custom-amplified speech stimuli was recorded using a Bruel and Kjaer 4819 half-inch microphone. The microphone was positioned in the right ear of the Knowles Electronic Manikin for Acoustic Research (KEMAR). The concatenated stimuli were presented to KEMAR's right ear using the same Sennheiser 280 Pro earphones that were used during testing. The root mean square (rms) SPL in third-octave bands of the top 10% ($L_{z_{max}}$) and the bottom 10% ($L_{z_{min}}$) were measured using the Bruel and Kjaer Type 2250 sound level meter. The AAI was calculated using a locally developed MATLAB computer program. The procedure for computing AAI (described below) differed slightly for the linear versus compression conditions.

The AAI for the linear condition was calculated using recommendations from Stelmachowicz et al (1994), shown below in Equation 2:

$$AAI = \left[\sum_{i=1}^{18} I_i (SL - LIMIT) \right] / 30 \quad (2)$$

I = band where I represents the third-octave band frequency importance weighting functions for nonsense syllables (American National Standards Institute [ANSI], 1997). SL represents the calculated third-octave band-centered sensation levels (linear). SL was computed using the following formula (Equation 3):

$$SL = (Amplified LTASS + 12) - (AIMAP) \quad (3)$$

Amplified LTASS represents the measured (i.e., $Lz_{\min}$ and $Lz_{\max}$) speech levels. AIMAP represents the third-octave dB SPL thresholds. The limit was calculated using the following formula (Equation 4):

$$Limit = (Amplified\ LTASS + 12) - (SSPL90) \quad (4)$$

SSPL90 represents the individually measured LDLs converted from octave to third-octave centered bands.

The AAI values for the compression conditions were calculated using the following formula (Equation 5):

$$AAI = \left[\sum_{i=1}^{18} I_i (SL - LIMIT) \right] / RANGE \quad (5)$$

RANGE represents the dynamic range of the speech signal. It was calculated as $30/MCR$.

MCR represents the mean nominal speech compression ratio from Figure 1B in Stelmachowicz et al (1994). The MCRs were 2.9 for the moderate compression condition and 8.9 for the extreme compression condition.

The sensation levels were calculated using the following formula (Equation 6: third-octave band sensation level [compression]):

$$SL = (Amplified\ LTASS + 12/MCR) - (AIMAP) \quad (6)$$

The limit was calculated using this formula (Equation 7: Limit [Compression]):

$$Limit = (Amplified\ LTASS + 12/MCR) - (SSPL90) \quad (7)$$

An AAI value of 0 implies that none of the speech signal is audible to the listener. An AAI value of 1.0 implies that the entire spectrum of the speech signal is audible to the listener. The AAI values were used to ensure that the test stimuli had similar and acceptable audibility (as might occur in a clinical hearing-aid fitting) across the three test conditions.

WMC

WMC was measured using a computerized version of the reading span test (RST) by Rönnerberg et al (1989). In this test, listeners were instructed to read an onscreen display of a set of sentences. Each sentence was presented visually on a computer monitor in sets of two-word pairs. At the end of each sentence presentation, a pause was introduced and listeners were instructed to state whether the sentence made sense (i.e., semantically). The examiner recorded the listener's response. The sentence sets increased from two sentences per set to six sentences per set. At the end of a single set of sentences (i.e., three, four, five, or six sentences), listeners were asked to recall either the first or last word of all the sentences in

the presented set. Participants were instructed verbally, and they were trained with a practice set of three sentences. The test was administered after the practice sentences. A total of 54 sentences were presented. Half (i.e., 27) of these sentences were semantically correct, and the other half were syntactically correct but semantically incorrect. Scores were based on the total number of words correctly recalled.

Two main methods are used for administering the RST (Engle et al, 1992; Conway et al, 2005): administrator-controlled timing and participant-controlled timing. The participant-controlled method allows listeners to control the processing time between presentations of each sentence. The administrator-controlled methods only permit readers to use a set amount of time (typically 1.75 sec) to read each sentence. A study by DeNeys et al (2002) tested 424 listeners using Dutch versions of an administrator-controlled and a computerized, participant-controlled method of the operation span task. They reported that when listeners were permitted as much time as needed to read and respond to each sentence, listeners generally performed better with the participant-controlled timing method, but scores correlated ighly ($r = .70$) between the two methods. These investigators noted that a fixed-presentation time may be advantageous for some listeners who can read the sentence quickly and have additional time to “rehearse” or use another recall strategy, whereas some other listeners may not have enough time to finish reading the entire sentence in the allotted time. For the current study, the participant-controlled timing method was chosen versus the administrator-controlled timing method to accommodate differences in reaction times across the listeners and control for floor effects in listeners with slower reaction times.

Spectral Resolution

Spectral resolution was measured using a modified version of the abbreviated version of the notched-noise procedure originally developed by Stone et al (1992) and adapted from Leek and Summers (1996).

Stimuli

The simultaneous masking notched-noise method was used to measure listeners' auditory filter bandwidths at 2000 Hz. All test stimuli were digitally generated using a sampling rate of 48.8 kHz. The probe signal (Ps) was a digitally generated 360 msec pure tone at 2000 Hz with 25 msec cosine ramped rise-and-fall times. The masker was a 460 msec noise with two noise bands that symmetrically or asymmetrically flanked the probe signal to create various spectral notch widths. The normalized frequency of the lower notch width was defined as

$g_l = \frac{(\dot{f}_l - f_c)}{f_c}$, and the upper notch width was defined as $g_u = \frac{(\dot{f}_u - f_c)}{f_c}$; f_l represents the edge of the lower noise band, and f_u represents the edge of the upper noise band. The lower and upper edges of the noise were set at $\pm 0.8 \times f_c$ (i.e., 400 and 3600 Hz). A total of six notch width configurations were used. Four of the notch edges were positioned at symmetric normalized frequency units of 0, 0.1, 0.2, and 0.4. Two of the notch edges were positioned at asymmetric normalized frequency units of 0.2, 0.4 and 0.4, 0.2 for the lower and upper notch widths, respectively.

Procedure

Listeners were instructed to detect a 360-msec pure-tone probe signal ($P_s = 2000$ Hz) that was positioned symmetrically and asymmetrically within a spectral notch. A two-interval, two-alternative forced-choice procedure was used. Both intervals had the masking noise, but only one of the two intervals had the tone positioned in the temporal center of the masker noise. Each listener was trained using a practice trial with symmetric and wide spectral notches (i.e., $g_l = 0.4$; $g_u = 0.4$). Correct-answer feedback was provided during the practice and testing sessions. The probe signal was presented at a fixed level of 10 dB SL (re: dB SPL threshold), and masker level was adaptively varied to obtain masked thresholds using a three-down/one-up adaptive tracking (Levitt, 1971). The step size was 7.5 dB for the first 4 reversals and was reduced to 2 dB for the remaining 10 reversals. Threshold was determined as the mean masker level for the last six reversals. A block was defined as a single threshold measurement. Testing included randomized presentations of 2 blocks of 14 reversals for each of the 6 notch widths.

The roex (p, r) model (Patterson et al, 1982) and the Polyfit program by Rosen and colleagues (Rosen and Baker, 1994; Rosen et al, 1998) were used to estimate the filter parameters and the bandwidth of listeners' auditory filter in equivalent rectangular bandwidths (ERBs). This procedure estimates the shape of an individual's auditory filter by fitting an n th-order polynomial function to the threshold curve that relates power in dB SPL/Hz of the masker at threshold to the distance between the noise edge from the center frequency (i.e., g) and then taking its derivative. The roex (p, r) model allowed independent parameters for the lower (i.e., p_l) and the upper (i.e., p_u) skirts, and the dynamic range (r) was set the same for both sides. The ERB of an auditory filter is defined as the width of a rectangular filter whose height equals the peak gain of the filter and which passes the same total power as the filter (given a flat spectrum input such as white noise or an impulse). Each listener's normalized ERB was calculated by dividing the Polyfit-estimated ERB by the center frequency (f_c) of the probe signal.

Results

Participants

Listeners classified into mild to moderate and moderate to severe hearing loss groups were statistically similar in: age [$t(26) = 0.438$, $p = 0.665$]; MMSE scores [$t(26) = -0.699$, $p = 0.491$]; and LDLs for speech [$t(26) = 0.652$, $p = 0.527$].

Spectral Resolution

In general, the listeners with mild to moderate hearing loss had significantly wider filter bandwidths compared with the listeners with moderate to severe hearing loss [$t(26) = -2.185$, $p = 0.049$].

WMC

Listeners with mild to moderate and moderate to severe hearing loss groups did not differ in their WMC scores for total number of words recalled (RST) [$t(2,26) = 1.099$, $p = 0.282$].

Table 1 shows RST score means and SDs for all listeners as well as the subgroups of listeners with mild to moderate and moderate to severe hearing loss.

Audibility Benefit

Improvement in audibility was defined as “audibility benefit,” and it was computed as the difference in AAI values between the linear and the compression conditions for each individual. Mean audibility benefit values were similar across (a) linear minus moderate compression, (b) linear minus extreme compression, and (c) extreme compression minus moderate compression, respectively, for the listeners with mild to moderate hearing loss [$(M = -0.07, -0.07, -0.01)$, ($SD = 0.09, 0.09, 0.02$)] and the listeners with moderate to severe hearing loss [$(M = -0.05, -0.09, -0.04)$, ($SD = 0.08, 0.11, 0.12$)]. Analysis of variance for the dependent variable audibility benefit showed that the interaction between amplification condition and degree of hearing loss was not significant [$F(2,26) = 0.602$, $p = 0.492$]. In other words, both listener groups received a similar improvement in audibility for compression compared with linear amplification.

Overall Scores

To stabilize the variance, absolute scores were transformed to rationalized arcsine units (RAUs) (Studebaker, 1985; Sherbecoe and Studebaker 2004). All statistical analyses were conducted using the RAU transformed speech scores. A two-way mixed-model repeated-measures analysis of variance was performed to evaluate the effect of amplification condition on speech recognition scores for the three different amplification conditions. The main question was whether compression amplification resulted in lower overall scores compared with linear amplification. We also evaluated whether the effect of compression amplification on overall scores was different for listeners with mild to moderate hearing loss compared with listeners with moderate to severe hearing loss. The dependent variable was overall speech recognition scores; the within-subject independent variable was amplification condition (i.e., linear, moderate compression, and extreme compression amplification). The between-subject independent variable was degree of hearing loss (i.e., mild to moderate and moderate to severe).

Mean overall scores and SDs are shown in Figure 2. Individual scores are shown in Figure 3. These figures show that overall speech recognition scores decreased for moderate and extreme compression compared with linear amplification for both listener groups. For all listeners, the interaction between amount of hearing loss and amplification was not significant [$F(2,26) = 1.32$, $p = 0.275$]. In other words, listeners with mild to moderate and listeners with moderate to severe hearing loss showed the same pattern of poorer performance with moderate and extreme compression amplification conditions, compared with the linear amplification condition. The main effect of amplification condition was significant [$F(2,26) = 29.079$, $p < 0.001$]. The main effect of hearing loss was also significant [$F(1,26) = 17.176$, $p < .001$]. Post hoc paired-sampled t -tests revealed that scores for the linear condition were significantly higher than the moderate compression condition [$t(27) = 3.546$, $p < 0.01$], and for the extreme compression condition [$t(26) = 6.578$, $p < 0.001$].

Regression Analysis on Overall Distortion Scores—Stepwise multiple linear regression analysis was used to determine whether spectral resolution, WMC, and audibility benefit predicted susceptibility to temporal envelope distortion. Overall distortion scores were determined by computing the difference in recognition scores for (a) moderate compression minus linear, (b) extreme compression minus linear, and (c) extreme compression minus moderate compression. The independent variables were composite spectral resolution, working memory, and audibility benefit. Audibility benefit was defined as the change in audibility for (a), (b), and (c), respectively. Across all listeners, the regression model was a significant predictor of overall temporal envelope distortion scores [$R^2 = 0.194$, $F(3,80) = 6.411$, $p = 0.001$], the regression coefficients, standard error of the standardized coefficients, and standardized coefficients are listed in Table 2. In summary, the regression analysis showed that spectral resolution, working memory, and audibility benefit each contributed to the model predicting overall temporal envelope distortion scores, with audibility benefit contributing the most.

Regression Analysis on Distortion Scores for Consonant Features—Trial-by-trial responses were subclassified as consonant place of articulation scores, manner of articulation scores, and voicing scores using sequential information feature analysis, originally developed by Miller and Nicely (1955). Feature analysis evaluates perceptual confusions based on specific linguistic features by reconstructing a composite confusion matrix into smaller submatrices within a specific linguistic category. The covariance between the input stimulus and a listener's response is the relative transmitted information (RTI) between input and response, where RTI values range from 0–1. An RTI of 1 implies a perfect correlation between stimulus and response (i.e., optimal transmission of information between input stimulus and the listener's response), and 0 implies no correlation or poor transmission of information. In the context of speech recognition, an RTI of 1 implies that the listener correctly identified the feature (e.g., place) 100% of the time. An RTI of 0 implies that the listener did not correctly identify the specific consonant feature.

To understand the effect of temporal envelope distortion for specific consonant features, distortion scores for consonant features (i.e., place, manner, and voicing) were computed as the difference scores for (a) moderate compression minus linear, (b) extreme compression minus linear, and (c) extreme compression minus moderate compression (Fig. 4). Similar to the overall score analysis described above, linear regression was used to determine the role of spectral resolution, working memory, and audibility benefit in predicting feature distortion scores for the three main consonant features. The dependent variables were distortion scores (i.e., difference in RTI scores) for consonant place of articulation, manner of articulation, and voicing.

For all listeners, the regression analyses significantly predicted feature distortion scores for consonant place of articulation [$R^2 = 0.136$, $F(3,80) = 4.212$, $p = 0.008$]; manner of articulation [$R^2 = 0.228$, $F(3,80) = 7.8734$, $p = 0.000$]; and voicing [$R^2 = 0.123$, $F(3,80) = 3.732$, $p = 0.014$].

Because we were also interested in group differences, we evaluated this regression model on each listener group. For listeners with *mild to moderate hearing loss*, this model did not

predict distortion scores for place of articulation [$R^2 = 0.007$, $F(3,41) = 0.103$, $p = 0.958$]; manner of articulation [$R^2 = 0.095$, $F(3,41) = 1.443$, $p = 0.244$]; and voicing [$R^2 = -0.100$, $F(3,41) = 1.525$, $p = 0.222$]. For listeners with *moderate to severe hearing loss*, this model predicted distortion scores for place of articulation [$R^2 = 0.475$, $F(3,35) = 10.551$, $p < 0.001$]; manner of articulation [$R^2 = 0.418$, $F(3,35) = 8.394$, $p < 0.001$]; and voicing [$R^2 = 0.399$, $F(3,35) = 7.745$, $p < 0.001$]. The regression coefficients, standard error of the standardized coefficients, and standardized coefficients are listed for place, manner, and voicing distortion scores in Tables 3–5, respectively.

Discussion

Spectral Resolution and Susceptibility to Distortion

The current study followed work by Davies-Venn et al (2009) and evaluated the role of spectral resolution in explaining variance in listeners' susceptibility to temporal envelope distortion. Our working hypothesis was that the listeners with poor spectral resolution would show the greatest susceptibility to temporal envelope distortion. Results showed that listeners with moderate to severe hearing loss had significantly poorer spectral resolution compared with listeners with mild to moderate hearing loss. For listeners with moderate to severe hearing loss, spectral resolution was a significant predictor of susceptibility to temporal envelope distortion for consonant manner of articulation. When we consider that consonant manner is primarily conveyed by the temporal envelope (Rosen, 1992), these results suggest that the listeners with poor spectral resolution were more dependent on temporal envelope cues and distorting these cues was most detrimental for them.

Working Memory and Susceptibility to Distortion

To process speech in continuous discourse, a listener has to carry out several operations such as (1) detect the signal and perform acoustic analysis of salient cues, (2) map the signal to his or her reservoir of stored phonemic categories, (3) store “old” information and combine with incoming new information, and (4) map stored phonemic information into meaningful discourse (Hickok and Poeppel, 2007). According to Wong et al (2009), the demand on cognitive resources required to execute all of these requisite stages increases as the listening environment becomes more challenging (e.g., noise or distortion). Working memory tasks, such as the RST used here, require simultaneous semantic processing, temporary storage, and manipulation of old and new information and have been used to assess abilities relevant to communication under adverse conditions.

The finding that working memory was a significant predictor of susceptibility to temporal envelope distortion for listeners with moderate to severe hearing loss is consistent with recent physiologic and behavioral research studies on the role of central processing in modulating the perceptual effects of distortion (e.g., Lunner and Sundewall-Thorén, 2007). Distortion can be classified as limitations of peripheral processing, such as signal processing from amplitude or spectral compression; or as signal-related distortions, such as presenting speech in noise. In general, when listeners are tested in less challenging situations, the role of central processing is reduced compared with when they are tested in more adverse situations. Recent physiologic studies have shown that listeners who can recruit a wider

network of prefrontal cortical activity to compensate for listening in adverse environments generally perform better than listeners who do not adapt in a similar manner (Hwang et al, 2007; Wong et al, 2009). Indeed, Wong et al (2009) also reported that for both young and older listeners, the ability to recruit a greater region of cortical activity had a significant correlation with behavioral performance for speech-processing tasks in noise. They concluded that “cortical compensation” for limitations was a predictor of behavioral performance for young and older listeners. Further studies are needed to understand the exact mechanism and interplay between cognition and peripheral auditory processing. Such information may aid design of strategic rehabilitation efforts, especially training and aural rehabilitation programs for listeners with hearing loss, many of which have shown mixed results until now.

Audibility and Susceptibility to Distortion

Finally, the role of audibility needs to be considered. For all of the regression analyses performed, audibility was at least one of the significant predictors of temporal envelope distortion. Several investigators have shown that performance with compression amplification is superior to linear amplification, but only in the cases with a substantial improvement in audibility (e.g., Davies-Venn et al, 2009; Kam and Wong, 1999). At conversational and higher speech levels, the improvement in audibility provided by compression amplification is not as substantial. We suggest that audibility benefit modulates the distortive effect of flattening the temporal envelope of speech. However, the effect was smaller for listeners who had a greater improvement in audibility with compression compared with linear amplification. In this study, all listeners performed worse with compression compared with linear amplification.

Restoring audibility is the primary goal of rehabilitation for listeners with hearing loss. Despite significant advances in hearing-aid design such as multichannel instruments, it is unlikely that we can attain equivalent audibility across all listeners with similar audiograms. Methods used to equate audibility experimentally (e.g., using a threshold-equalizing or threshold-matching noise (Dubno and Schaefer, 1992) or clinically (e.g., using multichannel hearing instruments that allow fine adjustments in frequency gain response) introduce other sorts of distortions from noise or spectral envelope distortions (e.g., Bor et al, 2008).

Summary and Conclusions

In summary, although the settings used in the current study (i.e., high compression ratios and earphones) limit generalizations to direct clinical application, the findings from the current study support a conscientious effort to improve audibility while minimizing distortion as the first priority of rehabilitation for listeners with hearing loss. The results from this study suggest that when audibility is adequately controlled, measuring spectral resolution may identify the listeners who are most susceptible to compression-induced distortions. Working memory appears to modulate the negative effect of these distortions for listeners with moderate to severe hearing loss.

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Abbreviations

AAI	Aided Audibility Index
EDI	Envelope Distortion Index
ERB	equivalent rectangular bandwidth
KEMAR	Knowles Electronic Manikin for Acoustic Research
LDL	loudness discomfort level
MMSE	Mini-Mental State Examination
NAL	National Acoustic Laboratories
PTA	pure-tone average
RAU	rationalized arcsine units
RST	reading span test
RTI	relative transmitted information
vCv	vowel-consonant-vowel
WMC	working memory capacity
WDRC	wide dynamic range compression

Figure 1.

The top two panels show mean amplitude envelope for the phoneme "azha" with linear amplification (solid line) and "clinical" compression amplification settings (dashed line). The two bottom panels show mean amplitude envelope for linear amplification (solid line) and moderate compression amplification (dashed line, left panel) and extreme compression (dashed line, right panel) for the same phoneme. Time (msec) is on the x-axis, and normalized amplitude (dB) is on the y-axis. The EDI is also stated in each panel.

Figure 2. Mean overall scores (%) for listeners with mild to moderate hearing loss (filled circles) and listeners with moderate to severe hearing loss (open circles). The x-axis represents the different amplification conditions. The y-axis represents overall percentage correct scores transformed to RAU. The lines represent ± 1 SE.

Figure 3.

Overall percentage correct scores for listeners with mild to moderate hearing loss (filled) and listeners with moderate to severe hearing loss (open). Symbols above the unity line show that listeners performed better with linear amplification compared with compression amplification. This figure shows that most listeners performed better with linear compared with moderate and extreme compression amplification.

Figure 4.

Mean RTI for place, manner, and voicing for linear (gray bars), moderate compression (white bars), and extreme compression (black bars). Listeners with mild to moderate hearing loss are shown on the left panel, and listeners with moderate to severe hearing loss are shown on the right panel. The error bars represent ± 1 SE.

Table 1
Mean Audiometric Thresholds (dB HL), PTA, LDL, Age, MMSE, RST Scores (%), Normalized ERB, and Hearing-aid Experience for Listeners with Mild to Moderate and Moderate to Severe Hearing Loss

Listener Group	250	500	1000	2000	3000	4000	6000	8000	PTA	LDL	Age	MMSE	RST	NormERB	Hearing-aid Use
Mild-Moderate															
Mean*	31.0	34.3	40.3	45.7	48.3	52.3	52.3	59.3	39.5	106.0	65.9	29.1	80.8	0.6	9.3
SE	2.6	2.4	2.5	2.4	2.8	2.5	2.4	2.9	1.8	1.8	4.3	0.3	2.6	0.1	2.1
Moderate-Severe															
Mean [†]	55.8	59.6	65.4	67.7	67.3	68.1	66.4	71.5	63.0	104.0	63.0	29.4	76.6	1.7	20.0
SE	1.8	1.6	2.1	1.7	1.6	1.8	2.5	3.6	3.2	3.2	1.9	0.2	2.8	0.5	4.2

* n = 15 for listeners with mild to moderate hearing loss;

[†] n = 13 for listeners with moderate to severe hearing loss.

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Table 2
Summary of Stepwise Regression Analysis for Variables Predicting Overall Temporal Envelope Distortion Scores (n = 28)

Variable	All			Mild to Moderate			Moderate to Severe		
	B	SE	B	B	SE	B	B	SE	B
Spectral resolution	-1.64	0.760	-0.227*	-2.117	6.236	-0.060	-2.142	0.645	-0.379**
Working memory	-0.224	0.102	-0.237*	-0.055	0.163	0.059	-0.341	0.116	-0.336**
Audibility benefit	-43.09	10.96	-0.406***	5.678	23.09	0.047	-63.35	10.14	-0.669***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table 3
Summary of Stepwise Regression Analysis for Variables Predicting Consonant Place of Articulation Distortion Scores for Listeners with Mild to Moderate Hearing Loss (n = 15) and Listeners with Moderate to Severe Hearing Loss (n = 13)

Variable	All			Mild to Moderate			Moderate to Severe		
	B	SE	B	B	SE	B	B	SE	B
Spectral resolution	-0.019	0.010	-0.211*	0.019	0.082	0.041	-0.024	0.009	-0.353**
Working memory	-0.001	0.001	-0.125	0.001	0.002	0.080	-0.002	0.002	-0.187
Audibility benefit	-0.450	0.142	0.339**	0.130	0.303	0.082	-0.679	-0.139	-0.598***

* Approaching marginal significance $p = 0.055$.
** $p < 0.01$.
*** $p < 0.001$.

Table 4
Summary of Stepwise Regression Analysis for Variables Predicting Consonant Manner of Articulation Distortion Scores for Listeners with Mild to Moderate Hearing Loss (n = 15) and Listeners with Moderate to Severe Hearing Loss (n = 13)

Variable	All			Mild to Moderate			Moderate to Severe		
	B	SE	B	B	SE	B	B	SE	B
Spectral resolution	-0.023	0.010	-0.234*	-0.033	0.002	0.270	-0.034	0.013	-0.364*
Working memory	-0.001	0.001	-0.064	0.003	0.002	0.270	-0.003	0.002	-0.158
Audibility benefit	-0.651	0.147	-0.446***	-0.001	0.228	-0.001	-0.858	0.203	-0.544***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table 5
Summary of Stepwise Regression Analysis for Variables Predicting Consonant Voicing Distortion Scores for Listeners with Mild to Moderate Hearing Loss (n = 15) and Listeners with Moderate to Severe Hearing Loss (n = 13)

Variable	All			Mild to Moderate			Moderate to Severe		
	B	SE	β	B	SE	β	B	SE	β
Spectral resolution	-0.008	0.010	-0.089	-0.139	0.079	-0.298	-0.012	0.002	-0.122
Working memory	-0.001	0.001	-0.044	0.003	0.002	0.219	-0.001	0.002	-0.122
Audibility benefit	-0.475	0.145	-0.353**	-0.146	0.293	-0.091	-0.686	0.149	-0.605***

**
 $p < 0.01$.

 $p < 0.001$.