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Temporal Resolution with a Prescriptive Fitting Formula

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Abstract

Purpose—Previous work using laboratory-based paradigms documented that WDRC may improve gap detection compared to linear amplification. The purpose of this study was to measure temporal resolution using WDRC fit with compression ratios set for each listener's hearing loss.

Method—Nineteen adults with mild-to-moderate hearing loss fitted with WDRC or linear amplification set to a prescriptive fitting method participated in this study. Subjects detected amplitude modulations and gaps. Two noise carriers were used: narrowband (1995–2005 Hz) or broadband (100–8000 Hz).

Results—Small differences between WDRC and linear amplification were observed in the measures of temporal resolution. Modulation detection thresholds decreased by a mean of 0.7 dB with WDRC compared to linear amplification. This reduction was observed for both carrier types. Gap detection thresholds did not differ between the two amplification conditions.

Conclusions—WDRC set using a prescriptive fitting method with individualized compression ratios had a small, but statistically significant effect on measures of modulation thresholds. Differences were not observed between the two amplification conditions for the measures of gap detection. These findings contrast with previous work using fixed compression ratios, suggesting that the effect of the fitting method on the compression ratio should be considered when attempting to generalize the effect of WDRC on temporal resolution to the clinic.

Speech recognition may depend on the ability of the listener to resolve the temporal features of a stimulus (e.g. Shannon et al. 1995). Temporal resolution refers to a listener's ability to detect changes in acoustic stimuli over time. Given that temporal resolution is related to speech recognition (Luo, Fu, Wei, & Cao, 2008; Gordon-Salant & Fitzgibbons, 1993; Helfer & Vargo, 2009) it may be possible to adjust the hearing aid response not only to achieve audibility but also to optimize temporal resolution. The present experiment examined temporal resolution with hearing-aid amplification fit using a prescriptive method.

Prescriptive fitting methods ameliorate the effect of hearing loss on a listener's dynamic range. A listener's dynamic range of hearing is the difference in dB between the listener's

hearing threshold and upper limit of comfort. Compared to listeners with normal hearing (NH), listeners with hearing loss (HL) have an elevated hearing threshold coupled with a close-to-normal upper limit of comfort (Ricketts & Bentler, 1996). The dynamic range available to a listener can be increased with wide dynamic range compression (WDRC) by decreasing the gain as the input level increases, which is sometimes referred to as input-controlled compression (e.g. Villchur 1973). In contrast to WDRC, linear amplification provides the same gain for all input levels up to the listener's upper limit of comfort. Compared to linear amplification, WDRC can improve audibility of low-level sounds while preventing high-level sounds from exceeding a listener's upper limit of comfort, therefore increasing a listener's dynamic range of hearing (Jenstad, Pumford, Seewald, & Cornelisse, 2000).

Fitting methods are designed to restore audibility, which is a frequency domain construct; however the use of WDRC to compensate for a listener's reduced dynamic range will affect the temporal properties of the output signal. This effect can be quantified by measuring the modulation depth, which is the change in signal level over a specified time interval. In general, WDRC reduces the modulation depth of the output signal relative to the input signal. In contrast, linear amplification maintains the modulation depth (Braidia, Durlach, De Gennaro, Peterson, & Bustamante, 1982; Moore, Stone, & Alcantara, 2001; Stone & Moore, 1992). The reduction in depth depends on the WDRC settings. For example, the compression ratio is a setting that specifies the change in output level divided by the change in input level. A 2:1 compression ratio means that for every 2 dB increase in the input level, there is a 1 dB increase in the output level. Increasing the compression ratio decreases the change in output level for a given change in the input signal level. Therefore, increasing the compression ratio decreases the modulation depth. The reduction in modulation depth also depends on the modulation depth of the input signal. Larger modulation depths are decreased by a greater amount than smaller depths, due to the attack and release time of WDRC. For a more detailed review see Stone and Moore (1992).

Perceptually, WDRC has been shown to have effects on temporal resolution. Gap detection thresholds depend on the modulation depth of the carrier signal. Specifically, gap detection thresholds improve for carrier signals with less modulation depth than those with greater modulation depth (Glasberg & Moore 1992). This is likely due to the modulations of the carrier signal interfering with a listener's ability to detect the change in level that occurs with the gap. One method to manipulate the modulation depth of the input signal is to vary the bandwidth of Gaussian noise. Narrowband noise (NBN) contains greater modulation depth than broadband noise (BBN: see Figure 1). Accordingly, WDRC should decrease the modulation depth more for NBN than BBN. The expected result is that WDRC improves gap detection thresholds for a NBN carrier, but not a BBN carrier, by reducing the modulation depth of the carrier signal. However, this may be an oversimplification; it could be the case that the gap would also be altered by the time constraints of compression, the duration of the gap, and the stimulus level of the carrier signal.

Glasberg and Moore (1992) measured gap detection thresholds for three NH listeners and four listeners with HL. The gap detection thresholds were measured using instantaneous compression. They varied the compression ratio (1.0 to 2.0) and the bandwidth of the carrier

signal (10 to 500 Hz). The sensation level was fixed. For a compression ratio of 1.5 or greater and a bandwidth less than 100 Hz, gap detection thresholds were better with WDRC compared to linear amplification. That study was followed with a later study using a wearable hearing aid that was available on the market at that time (Moore et al. 2001). The hearing aid was set using the manufacturer's default settings, except that the compression ratio was adjusted to 2.0. The investigators improved gap detection thresholds with WDRC compared to linear amplification for the listeners with HL but not for the listeners with NH. It was unclear why the discrepancy between groups occurred. It is possible that the small number of subjects per group accounted for the lack of a significant difference (n of 2–3). Alternatively, it is known that the actual output of a hearing aid can be 10–15 dB less than the manufacturer's predicted output (Aarts & Caffee, 2005; Hawkins & Cook, 2003). Because the predicted output is unreliable, it is unknown if the desired compression ratio of 2.0 in Moore et al. (2001) was achieved; if not, it could also account for the lack of a significant difference.

It is also of interest to determine whether the ability to perceive amplitude modulations is affected by WDRC. An amplitude modulated (AM) signal consists of a carrier signal that is sinusoidally modulated. WDRC should reduce the modulations of an AM signal, likely causing poorer thresholds when compared to linear amplification. While we are unaware of studies that examined AM detection in quiet, Shen and Lentz (2010) measured AM detection thresholds in the presence of an AM interferer. The interferer (2140 Hz) was spectrally separate from the target (500 Hz), which reduced the likelihood of energetic masking. Thresholds were measured under two conditions, with WDRC using a fixed compression ratio or linear amplification applied to the interferer. They found that relative to linear amplification, WDRC degraded thresholds.

While the studies mentioned above demonstrated that hearing-aid amplification can affect temporal resolution, the devices were set to a fixed compression ratio. Using a fixed compression ratio is an acceptable design if the aim is to determine if WDRC can improve gap detection thresholds, but that method is not representative of how the outputs of hearing aids are set in clinical practice. It is recommended that one set output levels of amplification using a prescriptive fitting method with measures of the real-ear output (ASHA, 1998; Valente et al. 2006). Real-ear output is measured by inserting a probe tube into the subject's ear canal. Attached to the probe tube is a microphone. The microphone is used to measure the output of the hearing aid near the tympanic membrane. The output of the hearing aid is then adjusted to match the output derived from the prescriptive fitting method.

Numerous prescriptive fitting methods are available. The current study used the Desired Sensation Level Input/Output Formula (DSL; Cornelisse, Seewald, & Jamieson, 1995), which is an older version of the current DSL algorithm (Scollie et al., 2005). The goal of the DSL algorithm is to fit speech within the dynamic range of hearing for each listener. The algorithm prescribes output target levels for speech of differing input levels. The prescribed outputs for different input levels are compressive, in that the increase in prescribed output is less than the change in the speech input level. Because the dynamic range of hearing for a listener decreases with increased severity of hearing loss, the prescribed compression ratios increase with the severity of the hearing loss. The prescribed output levels, then, could

influence the degree of compression that is being applied by a hearing aid. This contrasts with the fixed compression ratios that were used by Glasberg and Moore (1992), Moore et al (2001), and Shen and Lentz (2010). The current study extends previous work by determining the extent to which WDRC set using individualized compression ratios alters measures of temporal resolution.

In summary, listeners with HL have a reduced dynamic range. WDRC improves a listener's dynamic range of hearing by increasing gain for low-level signals while decreasing gain for high-level signals. WDRC decreases the modulation depth of the input signal whereas linear amplification maintains the modulation depth. The reduction in modulation depth is greater with increases in compression ratio. WDRC improves gap detection thresholds but can degrade AM detection thresholds compared to linear amplification. In previous studies, the compression ratio was set using a constant compression ratio. In practice it is recommended that the hearing aid be set using a prescriptive fitting method, with compression ratios that increase with the severity of the hearing loss. The extent to which a hearing aid set to a prescriptive fitting method alters measures of gap detection or AM detection is unknown. It is possible that using individualized compression ratios would be sufficient to alter AM detection and gap detection in the manner described. Alternatively, the prescribed compression ratios may be too small to alter perception. Relative to linear amplification, it was hypothesized that:

1. WDRC would improve gap detection thresholds for a NBN carrier. Gap detection thresholds would be equivalent for the BBN carrier.
2. WDRC would degrade AM detection thresholds for both carrier types.

METHODS

Subjects

Twenty adult subjects with symmetric mild-to-severe sensorineural hearing loss (25 to 75 dB HL from .25 to 4 kHz) were recruitedⁱ. An audiologist measured hearing thresholds (re ANSI 2004) using conventional audiometry (ASHA 2005) at octave frequencies from 250 to 8000 Hz. The mean hearing thresholds across subjects are shown in Figure 2. The mean age was 66 years and the range was 22 to 89 years. Eleven subjects were experienced users of WDRC hearing aids and the other subjects had never worn hearing aids. All subjects had normal middle ear status as measured via tympanometry (ASHA 1990), were native English speakers (self-report), and passed the Mini-Mental State Exam with a score of 24 or higher (maximum score 30; Folstein, Folstein, & McHugh 1975).

Data were collected at both the University of Washington and Northwestern University using similar equipment and procedures. Approval for this study was obtained from the Institutional Review Boards at both universities. Subjects signed an informed consent document and were reimbursed for their time.

ⁱOne subject did not complete the gap-detection test and another subject was excluded from the analysis because the hearing aid was not correctly programmed. The number of subjects was selected based on a power analysis (Bausell et al. 2002) with significance level of 0.05 and power of 0.80. Based on preliminary data and previous work, the expected effect size was 0.4. For this effect size 20 subjects were needed to achieve 80% power.

Hearing Aid Settings

Each subject was fit with binaural digital behind-the-ear hearing aids with 15 independent channels. Each channel was 500 Hz wide with slopes of 50 dB per octave. Each channel had an independent compression system that utilized both slow and fast time constants. Specified according to the ANSI (1996) standard, the attack time was 1 ms and the release time was 10 ms for a 2000 Hz pure-tone input. Each channel had a compression kneepoint, compression ratio, and maximum power output. Expansion was used below the kneepoint. The expansion ratio was 0.65 when linear amplification was used and varied between 0.5 and 0.7 across channels with compression amplification. DSL prescribes different kneepoints for varying frequencies. This can have the effect of introducing audibility difference between linear and WDRC. Although less realistic, to reduce audibility differences between WDRC and linear amplification the kneepoint was set to 30 dB SPL in all channels (Brennan & Souza, 2009). The examiner implemented two programs in each hearing aid. The first program was linear amplification with compression limiting and the second program was WDRC. The compression ratio was individually set for each subject's hearing loss based on DSL. Noise reduction, feedback suppression, and directional microphones were turned off for both programs. The hearing aids were attached to custom earmolds (acrylic, canal style with canal lock, and appropriate vent size that ranged from unvented to 3 mm).

To obtain a measure of signal level for each subject, the examiner inserted a small probe tube into the ear canal, inserted the hearing aid, and measured real-ear aided output using a Fonix 6500 or 7000 probe microphone system (Frye Electronics, Tigard, OR). To minimize the effects of standing waves, the probe tube was inserted 20 mm past the ear canal entrance, placing it within 5 mm of the tympanic membrane for the average adult ear canal length. For both hearing aid programs, real-ear aided output was adjusted as closely as possible to within 5 dB of the DSL i/o recommended output for a 60 dB SPL composite speech noise and for a 90 dB SPL swept pure tone. For the WDRC program the output was adjusted, as closely as possible, to the DSL recommended real-ear aided output for 50 and 70 dB SPL composite speech noise inputs. The mean output level at 1, 2, and 4 kHz is shown in Figure 3. The compression ratio was estimated for each participant at 1, 2, and 4 kHz from the real-ear output plots. The compression ratios are depicted in Table I. The compression ratio was lower at 4 kHz compared to 1 and 2 kHz because the hearing-aid gain was maximal for all input-levels at this frequency for many of the subjects.

To assess the fit-to-target, the mean root-mean-square (RMS) error was calculated and compared to data obtained by Cox and Alexander (1990)ⁱⁱ. In that study, 24 adults were fit with hearing aids using a prescriptive method. The RMS error from 250 to 4000 Hz was computed for each subject and the mean RMS error was found to be 7 dB. The mean RMS error for this study was 6 dB, suggesting that the achieved output was within the expected range. Polonenko et al. (2010) reported 95% confidence intervals from 5.8 to 8.4 dB across frequencies, which was within the mean error for this study. As an additional check, Bagatto et al (2011) computed fit to target data for the child version of DSL v5. The UWO

ⁱⁱOne subject's real-ear data were not saved due to an equipment error and that subject's data are not reflected in RMS error.

normative data from Bagatto et al (2011) contains the 95% confidence intervals for the speech intelligibility index as a function of the PTA for an input level of 65 dB SPL. Our output levels were based on an input level of 60 dB SPL, yet the speech intelligibility index fell within those 95% confidence intervals for all but three subjects.

Apparatus

Stimuli were presented at a sampling rate of 48 kHz via a Tucker-Davis RP-2 or RX-6 real-time processor, a PA5 attenuator, and a JBL LSR25P loudspeaker. The loudspeaker was located 1 m from the subject and at 0 degree azimuth. Stimuli were presented at 60 dB SPL and were calibrated to the RMS average for the narrowband noise and the broadband noise. All testing took place in a double-walled sound attenuated room that met standards for permissible noise levels during audiometric testing (ANSI 1991). Each subject completed the modulation-detection task and then the gap-detection task.

Temporal Resolution

Procedure—Gap and AM thresholds were estimated using a three-interval forced-choice task with a two-down one-up adaptive rule (Levitt 1971). For the AM detection task, the modulation depth was calculated as $20 \times \log_{10}(m)$, where m is the modulation index. The modulation depth started at 100% ($m = 1$, or 0 dB) and was initially varied by 5 dB and then by 2 dB after 4 reversals. The modulation depth never exceeded 0 dB. The gap duration started at 100 ms and initially varied by a factor of 1.4 and then by 1.2 after 4 reversals. Each block contained 14 reversals. For each task, subjects practiced 4 blocks for each carrier and then data were collected for an additional 4 blocks. The type of amplification and carrier order was randomized. For the modulation-detection task, threshold was taken as the mean modulation depth at the last 10 reversals, averaged across the blocks. For the gap-detection task, threshold was taken as the geometric mean gap duration at the last 10 reversals and then the geometric mean was calculated across the blocks.

Stimuli—The carrier signals were selected to represent a carrier and modulator that are present in speech, as follows. First, because the modulations in speech are dominated by slow modulation rates, modulation detection was measured at a 10 Hz modulation rate. Second, because the carrier signal for voiceless speech can be modeled as broadband noise, a broadband noise carrier was included. The center frequency for the narrowband carrier was 2 kHz, due to the relative importance of that frequency to speech understanding when compared to other frequencies. Stimuli were generated using MATLAB. The carrier was either broadband noise (100–8000 Hz) or narrowband noise (1995–2005 Hz) and the carrier duration was 250 ms with 10-ms raised-cosine ramps. For the modulation-detection task, the modulated signal was created by multiplying the carrier signal by a 10 Hz sinusoidal modulator $1 + m \times \sin(2 \times \pi \times 10 \times t)$ where m is the modulation index and t is time. Equating the RMS values of the stimuli eliminated intensity differences between the modulated and non-modulated stimuli.

For the gap-detection task, the methodology was similar to that used by Glasberg and Moore (1992). The carrier signal was multiplied by a signal with a gap that contained 0.5 ms cosine squared ramps. For the narrowband noise carrier, the spectral splatter caused by the gap was

masked using 50 dB SPL broadband noise (100–8000 Hz). Figure 1 shows time waveform plots of the carrier signals before and after amplification.

Modulation Depth

With the hearing aids in the examiner inserted a probe tube approximately 20 mm past the past the ear canal entrance and recorded the broadband noises carrier modulated at $m = 1$. The recordings were used to measure the modulation depth. The modulation depth was measured using a procedure similar to that utilized by Gallun and Souza (2008). A steady state portion of the recording was selected by removing the first and last 10 ms of each recording. The second step limited the stimuli in the carrier domain to a set of five octave-wide bands centered at 250, 500, 1000, 2000, and 4000 Hz. The third step extracted the modulation frequencies by half-wave rectifying each of the band-filtered signals and then low-pass filtering at 50 Hz. The next step estimated the modulation frequencies by down sampling each signal to 1000 Hz, zero-padding to extend the signal to 5 seconds, and then submitting to a Fast-Fourier Transform (FFT). The modulation depth was computed for each FFT bin by computing the energy in that bin and dividing it by the energy in the 0 Hz bin. This provided a normalized modulation depth value. Because the modulation rate used in this study was 10 Hz only the modulation depth at that rate was reported. While this model is simple it has been useful in describing the effect of WDRC on both the modulation depth and on speech recognition (Gallun and Souza, 2008; Souza and Gallun, 2010).

Statistics

The goal of this study was to determine if WDRC set using individual compression ratios alters measures of temporal resolution relative to linear amplification or alters the modulation depth. A two-way repeated-measures analysis of variance (ANOVA) was used to examine the effects of amplification and carrier type on the amplitude-modulation threshold, the gap threshold, and the modulation depth. In each case, the dependent variable was the modulation threshold, gap-detection threshold, or modulation depth. The independent variables were the amplification condition (WDRC, linear) and the carrier bandwidth (narrowband noise, broadband noise). For the modulation-depth analysis, an additional variable, the carrier frequency, was included. Sphericity was evaluated using Mauchly's Test of Sphericity and the degrees of freedom were adjusted using the Greenhouse-Geisser correction if the assumption of sphericity was violated. Post-hoc comparisons were made using Tukey's HSD test. This analysis determined if WDRC set to DSL altered measures of temporal resolution and, if so, if the effect was mediated by the carrier signal. It also quantified the effect on the modulation depth of the signal.

RESULTS

Temporal Resolution

The modulation-detection thresholds are plotted in Figure 4A. Better modulation thresholds are indicated by lower modulation depth (higher on the y-axis). There was a significant main effect of carrier bandwidth, $F(1, 18) = 293, p < 0.001, \eta^2 = .94$ with better modulation thresholds for the broadband carrier ($M = -16.5$ dB, $SD = 3.2$) than the narrowband carrier ($M = -5.2$ dB, $SD = 2.5$). There was also a significant main effect of the amplification type,

$F(1, 18) = 7.03, p = 0.016, \eta p^2 = .28$, with better modulation thresholds for the linear condition ($M = -11.3$ dB, $SD = 6.6$) than the WDRC condition ($M = -10.6$ dB, $SD = 6.4$). There was no interaction between amplification and carrier bandwidth $F(1, 18) = 0.002, p = 0.967, \eta p^2 < .01$.

The gap-detection thresholds are plotted in Figure 4B. The gap thresholds in ms were $\log_2$ transformed which resulted in a more normal distribution of thresholds. Better gap thresholds are indicated by shorter gap duration (higher on the y-axis). There was a significant main effect of carrier bandwidth, $F(1, 17) = 45, p = 0.001, \eta p^2 = .73$ with better gap thresholds for the broadband carrier ($M = 4.2$ ms, $SD = 1.2$) than the narrowband carrier ($M = 48.0$ ms, $SD = 51.9$). Neither the main effect of the amplification condition, $F(1, 17) = .63, p = 0.44, \eta p^2 = .04$, nor the interaction between amplification and carrier bandwidth, $F(1, 17) = .4, p = 0.549, \eta p^2 = .02$, were significant. These results show that listeners performed more accurately for both measures of temporal resolution with a broadband noise carrier than with a narrowband noise carrier. While mean amplitude modulation detection was better by .7 dB with linear amplification than with WDRC, the ability to detect a gap did not depend on the type of amplification.

Figure 5 shows the modulation depth using a 10 Hz modulator with linear and WDRC amplification, averaged across the two ears. Greater modulation depth is shown higher on the y-axis. There was a significant main effect of the amplification condition $F(1, 15) = 4.75, p = 0.046, \eta p^2 = .241$ with greater modulation depth with linear ($M = -.18$ dB, $SD = 1.53$ dB) than WDRC amplification ($M = -.35$ dB, $SD = 1.3$ dB). There was also a significant main effect of the carrier frequency $F(4, 60) = 30.066, p < 0.001, \eta p^2 = .667$, due to the modulation depth varying with the carrier frequency. The interaction between the amplification condition and the carrier frequency was significant $F(4, 60) = 29.555, p < 0.001, \eta p^2 = .663$. The post-hoc analysis showed a significantly greater modulation depth with WDRC for a carrier frequency of 250 Hz. In contrast, a significantly greater modulation depth occurred with linear amplification for the carrier frequencies 1, 2 and 4 kHz. The difference for a carrier frequency of 500 Hz was not significant. These results showed that for most of the carrier frequencies, WDRC reduced the modulation depth of the modulator when compared to linear amplification and this reduction was a mean of .17 dB. When averaged across the frequencies where the depth was significantly reduced with WDRC (1–4 kHz) the mean reduction was .39 dB.

DISCUSSION

Previous studies used fixed compression ratios to evaluate gap detection thresholds with amplification (Glasberg & Moore, 1992; Moore et al. 2001). The present study sought to evaluate whether WDRC as set using a prescriptive fitting method with compression ratios set for each listener's dynamic range altered measures of temporal resolution when compared to linear amplification. It was expected that WDRC would reduce modulation thresholds, improve gap detection thresholds for a narrowband noise carrier, and have no effect on gap detection thresholds for a broadband carrier. The null hypothesis was that WDRC would not alter these measures of temporal resolution due to the compression ratio not being sufficient to alter the modulation depth of the signal. This study found that WDRC

when compared to linear amplification reduced modulation detection thresholds by a modest (although statistically significant) .7 dB and that WDRC did not improve gap detection thresholds for either noise carrier.

The results support the existing literature to some extent. Shen and Lentz (2010) measured AM detection thresholds for a target at 500 Hz in the presence of an AM interferer centered at 2140 Hz. It was found that relative to linear amplification, WDRC degraded thresholds. Despite the difference in stimuli, both this study and Shen and Lentz found that compression degraded AM detection thresholds.

Some of the findings are not in agreement with previous literature. This study found that gap detection thresholds did not improve when using a narrowband noise carrier, in contrast to some of the previous work in this area (Glasberg & Moore, 1992; Moore et al. 2001). Glasberg and Moore found that instantaneous compression improved gap detection threshold for subjects with normal hearing and hearing loss. Moore et al. found that the fast compression relative to the slow compression used in that study improved gap detection thresholds for listeners with normal hearing but not for the listeners with hearing loss. This discrepancy across studies might have to do with the effective compression ratio that is applied when you use DSL. For example, Glasberg & Moore found that, when using instantaneous compression, a compression ratio of 1.5 or greater was necessary to improve gap thresholds. Additionally, the slower compression used in this study (1 ms attack, 10 ms release) and in Moore et al. (15 ms attack, 30 ms release) relative to that used in Glasberg and Moore could explain the disparate results. This suggests that the combination of compression settings inherent to the hearing aid and the use of the DSL algorithm likely contributed to the small mean reduction in modulation depth observed (.17 dB). The probable consequence of this was that a change in gap detection thresholds was not observed. While the compression ratios used in this study might have been too small to alter gap detection, these compression ratios were reflective of what individuals would receive with hearing aids. This study demonstrates that to understand how gap detection and modulation detection will be affected under real circumstances, it is necessary to examine these measures using ecologically valid methods.

It is also of interest to know if those subjects who had a higher compression ratio were more likely to show improved gap detection thresholds when compared to linear amplification. The following steps were taken to assess this: 1) the compression ratio at 2 kHz between the left and right ear was averaged, 2) the gap detection threshold for a narrowband carrier with linear amplification was subtracted from that obtained with WDRC (gap detection difference), 3) a scatter plot was constructed that compared the compression ratio to the gap detection difference, and 4) a linear regression analysis was completed, with the compression ratio at 2 kHz as the predictor variable and the gap detection difference as the dependent variable. The scatter plot did not reveal a relationship between the compression ratio and the gap detection difference. The linear regression was not significant $F[1,17] = 0.000, p = .987, R^2 < .001$. Thus this study did not find evidence that the compression ratio altered the gap detection threshold.

This study suggests that using WDRC fit with a prescriptive method has minimal effects on the modulation depth of the signal relative to linear amplification and consequently, measurements of temporal resolution. As evidence for this we refer to the findings depicted in Figures 4 and 5. Some researchers have put forth the viewpoint that compression should be used in order to improve a listener's ability to perceive gaps in speech (Glasberg & Moore 1992). In contrast, Plomp (1988) expressed the concern that compression could negatively affect measures of temporal resolution, and consequently, impair speech recognition by limiting a listener's ability to resolve the temporal information encoded in speech. Our findings suggest that compression set using a prescriptive fitting method might not be altering a listener's ability to perceive gaps and instead slightly worsening modulation thresholds. These findings lend support to the concerns first expressed by Plomp but not to those expressed by Glasberg and Moore.

Because WDRC has the potential to enhance temporal processing, it is possible that the methods used to fit hearing aids today are not optimized for temporal resolution. In future work it may be possible to adjust the hearing aid response not only to achieve audibility but also to optimize the temporal properties of the signal. In order to do this it would be necessary to better understand 1) how different methods for fitting hearing aids affect measures of temporal resolution and 2) how to modify existing fitting methods to improve temporal resolution. For example it might be possible to increase the individualized compression ratios, leading to improved gap detection thresholds. Because DSL v4 is similar to the pediatric version of DSL v5 (Scollie et al., 2005), we expect that the results obtained here likely extend to that of the pediatric version of DSL v5. It is not clear how the results of this study might extend to other prescriptive fitting methods, such as the adult versions of DSL v5, NAL-NL1, or NAL-NL2.

The conclusions drawn may be limited to the specific device used, to the low-kneepoint used, the specific measures of temporal resolution employed, and to listeners with mild to moderate degrees of hearing loss. For example, using greater degrees of hearing loss than was used in this particular study is expected to increase the compression ratio. The consequence is that greater changes to the modulation depth of the signal would be expected between conditions. Accordingly, it is expected that larger effects on measures of temporal resolution might occur.

CONCLUSION

These data indicate a significant but small reduction in temporal resolution for WDRC compared to linear amplification when measured with modulation detection and a lack of a difference when measured with gap detection. This demonstrates that clinically fit WDRC with individualized compression ratios is not having a large effect on measures of temporal resolutions. This is supported by the small change in the modulation depth that was measured for a modulated signal between WDRC and linear amplification.

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Figure 1.

Time waveform plots of the carrier signals before amplification (A and D), with linear amplification (B and E), and with compression amplification (C and F). Broadband noise is shown in panels A–C and narrowband noise with broadband masking in panels D–F. Recordings were for subject 17 in the left ear.

Figure 2.
Mean air conduction audiometric thresholds. Error bars represent one standard deviation.

Figure 3.
Hearing aid output. Dashed lines = 4 kHz. Dotted line = 2 kHz. Solid line = 1 kHz.

Figure 4.

Amplitude-modulation detection thresholds (panel A) and gap detection thresholds (panel B). For all panels better results are shown as higher on the y-axis. NBN = narrowband noise carrier, BBN = broadband noise carrier. Error bars represent one standard deviation.

Figure 5. Modulation depth with linear (unshaded boxes) and compression amplification (shaded). Error bars represent the 5th and 95th percentiles. The line represents the median and the filled circle the mean. The lower and upper line of each box represents the 25th and 75th percentiles, respectively.

Table 1

Compression ratios.

Subject		Compression Ratio					
ID	Left Ear			Right Ear			
	1 kHz	2 kHz	4 kHz	1 kHz	2 kHz	4 kHz	
1	1.1	1.2	1.1	1.3	1.5	1.3	
2	1.2	1.4	1.5	1.4	1.8	1.4	
3	NA	NA	NA	NA	NA	NA	
4	1.1	1.7	1.0	1.2	1.6	1.0	
5	1.6	1.0	1.5	1.3	1.0	0.8	
6	1.3	1.5	1.3	1.1	1.4	1.8	
7	1.8	1.7	1.1	1.9	0.9	1.1	
8	1.3	1.5	1.3	1.1	1.4	1.8	
9	2.1	1.7	1.1	1.3	1.3	1.0	
10	1.6	1.5	1.0	1.7	1.5	1.2	
11	1.6	2.0	1.3	1.3	1.5	1.2	
12	0.8	1.5	1.5	1.2	1.3	1.8	
13	1.6	1.5	1.6	1.4	1.5	1.1	
14	1.5	1.7	1.8	1.1	1.5	1.8	
15	1.3	1.9	1.4	1.0	1.4	1.6	
16	1.2	1.2	1.2	1.0	1.5	1.2	
17	1.8	1.8	1.2	1.8	1.5	1.2	
18	1.7	1.6	1.0	1.4	1.5	1.8	
19	1.3	1.4	1.1	1.2	1.2	1.0	
Mean	1.4	1.6	1.3	1.3	1.4	1.3	
SD	0.3	0.3	0.2	.3	.2	.3	

The compression ratio was calculated as $\frac{SPL_{70} - SPL_{50}}{20dB}$ where SPL_{70} and SPL_{50} are the output level for 70 and 50 dB SPL composite speech noise inputs, as measured with the Fonix probe microphone system. NA, not available due to error during the recording.