The influence of hearing-aid compression on forward-masked thresholds for adults with hearing loss

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This paper describes forward-masked thresholds for adults with hearing loss. Previous research has demonstrated that the loss of cochlear compression contributes to deficits in this measure of temporal resolution. Cochlear compression can be mimicked with fast-acting compression where the normal dynamic range is mapped to the impaired dynamic range. To test the hypothesis that fast-acting compression will most-closely approximate the normal ability to perceive forward-masked pure-tones, forward-masked thresholds were measured for two groups of adults (normal hearing, hearing loss). Adults with normal hearing were tested without amplification. Adults with hearing loss were tested with three different compression speeds and two different prescriptive procedures using a hearing-aid simulator. The two prescriptive procedures differed in the extent to which the normal dynamic range was mapped onto the impaired dynamic range. When using a faster compression speed with the prescriptive procedure that best restored the lost dynamic range, forward-masked thresholds for the listeners with hearing loss approximated those observed for the listeners with normal hearing. © 2015 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4932028>]

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I. INTRODUCTION

The loss of cochlear compression can explain why listeners with sensorineural hearing loss (SNHL) exhibit less recovery from the masker than listeners with normal hearing (NH) (Johannesen *et al.*, 2014; Oxenham and Bacon, 2003). Studies to date have compared listeners with NH and SNHL at either equal sensation level (SL) or sound-pressure level (SPL) (Desloge *et al.*, 2011; Festen and Plomp, 1983; Johannesen *et al.*, 2014; Nelson and Freyman, 1987; Schairer *et al.*, 2008) but have not determined if compression applied to the stimulus can improve recovery from masking in listeners with SNHL. This study examined changes in forward-masked thresholds with three compression speeds and two prescriptive procedures. Forward-masked thresholds and the amount of masking were compared between two groups of listeners: One with NH and one with SNHL, to determine the compression speed and prescriptive procedure that minimized group differences.

Forward masking may be affected by neural adaptation, temporal integration, and cochlear compression (Oxenham, 2001; Schairer *et al.*, 2008; Smith, 1979). Neural adaptation is the change in neural response to a constant stimulus and is greater with SNHL (Scheidt *et al.*, 2010). Scheidt and colleagues argued that both the inner hair cell synapse and the neural response itself might be responsible for neural adaptation. Neural adaptation could prevent a listener from detecting the target, due to decreased responsiveness immediately following the masker. Temporal integration is the accumulation of the neural response over time that occurs central to the cochlea (for a review see Schairer *et al.*, 2008). Temporal integration could contribute to forward masking by causing

overlap in the internal representation of the masker and the target. Cochlear compression is the decreased gain with increased input level that occurs on the basilar membrane (Ruggero *et al.*, 1997). While all three mechanisms may contribute to forward masking, this study examined the contribution of compression to forward masking in listeners with SNHL.

Reduced cochlear compression associated with SNHL results in reduced gain for both the masker and the target that follows the masker. For short time delays, the effect of SNHL is not as severe as for long time delays. This is because, at forward-masked threshold, the levels of the masker and target are similar. Therefore, the masker and the target receive the same amount of amplification. However, with longer time delays the target level at threshold is less than the masker level. At these lower levels, the loss of cochlear compression with SNHL results in a reduction in low-level gain and consequently a higher threshold of the target. Models of forward masking and combined backward and forward masking suggest that these changes in cochlear compression can explain differences in the amount of masking between listeners with NH and SNHL (Oxenham and Bacon, 2003; Oxenham and Moore, 1995).

Compression amplification can compensate for the loss of compressive nonlinearity that occurs with SNHL by applying increased gain as the input level decreases. Yet, studies that examined forward masking in listeners with and without SNHL did not test if providing compression to listeners with SNHL minimizes differences between these two groups but instead compared the two groups at equal SPL, equal SL, or by simulating hearing loss for listeners with NH (Desloge *et al.*, 2011; Festen and Plomp, 1983; Johannesen *et al.*, 2014; Nelson and Freyman, 1987; Schairer *et al.*, 2008). For a masker at a similar SPL, listeners with SNHL show higher

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forward-masked thresholds than listeners with NH but little, if any, difference remains when compared at an equal SL (Festen and Plomp, 1983; Glasberg *et al.*, 1987; Nelson and Freyman, 1987; Schairer *et al.*, 2008). Desloge *et al.* (2011) demonstrated that forward masking for listeners with SNHL could be simulated in listeners with NH using masking noise combined with expansion. This pattern of findings across studies may occur because less cochlear compression of the target occurs for the listeners with SNHL than for the listeners with NH, as argued by Johannesen *et al.* (2014) and others (e.g., Oxenham and Bacon, 2003).

The extent to which the reduced cochlear compression with SNHL is compensated for will depend on the compression speed and prescriptive procedure used. The faster the compression speed, the more quickly the hearing aid adjusts its gain to changes in the input level. Compared to an unaided condition, compression amplification will increase the level of both the masker and the target. For a target presented after a masker, a faster compression speed will increase the level of the target relative to the masker and consequently decrease forward masking. Because the auditory system has nearly instantaneous compression, it is hypothesized that fast compression will result in forward-masked thresholds for the participants with SNHL that are similar to those for participants with NH.

Different prescriptive procedures are available for setting the hearing-aid compression (e.g., Keidser *et al.*, 2011; Moore *et al.*, 2010; Scollie *et al.*, 2005) for a given degree of hearing loss. One way in which these procedures differ is the extent to which they map the normal dynamic range of hearing onto the impaired dynamic range. Figure 1 shows the prescribed output at 2 kHz for a given input level with child (line with long dashes) and adult (line with short dashes) versions of the Desired Sensation Level (DSL) i/o program (Scollie *et al.*, 2005). The adult version is based on the child version, with a gain and compression ratio reduction because adults find the child version to be too loud (Scollie *et al.*, 2005). As a consequence, a larger input dynamic range is mapped to the residual dynamic range for DSL-child than for DSL-adult (Fig. 1). Because the child version better maps the normal dynamic range to the impaired dynamic range, it also better reproduces the effects of cochlear compression.

The purpose of the present study was to measure forward-masked thresholds under hearing-aid amplification for listeners with SNHL. Three compression speeds were used to determine if, as hypothesized but not tested by others (Edwards, 2001; Laurence *et al.*, 1983; Moore, 1991), a faster compression speed measurably steepens the slope of the forward-masking recovery function. Two prescription procedures that differ in the extent to which they restore the normal dynamic range (adult and child versions of DSL) were used to determine if increased dynamic range, and hence cochlear compression, improves forward-masked thresholds. The effect of the prescriptive procedure was expected to interact with the time delay and compression speed, such that the procedure that better restored cochlear compression (DSL-child) would show a steeper slope of the forward-masking recovery function than a prescriptive procedure that did not fully restore cochlear compression (DSL-

FIG. 1. Prescribed output at 2 kHz for a hearing threshold of 74 dB SPL (solid horizontal line). DSL-child shown as a line with long dashes. DSL-adult shown as a line with short dashes. The upper limit of comfort is 118 dB SPL. The input dynamic range is larger with DSL-child (27 to 118 dB SPL) than with DSL-adult (36 to 118 dB).

adult). Forward-masked thresholds were also obtained, without amplification, for a group of listeners with NH and for four of the participants with SNHL. Data from listeners with NH and SNHL were compared to determine if fast compression with DSL-child approximated the forward-masked thresholds for the listeners with NH, as hypothesized. Any remaining differences in forward masking between the two groups would suggest that other mechanisms might contribute, such as temporal integration (Oxenham, 2001).

II. METHOD

A. Participants

Nine adults [median: 54 yrs, mean: 48 yrs, standard deviation (sd): 13 yrs, range: 20–58 yrs] with symmetric mild-to-severe SNHL and 9 adults with NH (median: 52 yrs, mean: 47 yrs, sd: 12 yrs, range: 21–60 yrs) participated. Each NH participant was age matched to within 5 yrs of a participant with SNHL. An audiologist measured hearing thresholds (re: ANSI, 2004) for all participants using conventional audiometry (ASHA, 2005) at octave frequencies from 250 to 8000 Hz (Fig. 2). All subjects were native English speakers. Data were collected at Boys Town National Research Hospital. Approval for this study was obtained from the Institutional Review Board. Participants consented to join the study and were reimbursed (\$15/h) for their time.

B. Stimuli

Stimuli were generated using a PC and custom MATLAB (2009b) (Mathworks, Natick, MA) scripts. The masker was a 70 dB SPL 2-kHz pure tone, 400 ms in duration with 2-ms ramps. The target was a 2-kHz pure tone, 20 ms in duration with 2-ms ramps. The target level was varied adaptively.

FIG. 2. Audiometric thresholds of the participants. Boxes represent the interquartile range and whiskers represent the 10th and 90th percentiles. For each box, the lines represent the median and filled circles represent the mean thresholds.

The target was presented without the masker and 0, 10, 80, and 100 ms after the masker (time delay). All durations, including time delays, were measured from the 0-amplitude points of the onset and offset ramps. Stimuli were calibrated by calculating the root-mean-square average in a 6 cc flat plate coupler using a Larson Davis System 824 sound level meter (Depew, New York).

C. Apparatus

Digital stimuli (22.05 kHz sampling rate) were converted to analog (Lynx Studio Technology Lynx Two B sound card, Costa Mesa, CA), routed via a MiniMon Mon800 monitor matrix mixer (Behringer, Germany), amplified with a PreSonus HP4 headphone distribution amplifier (Baton Rouge, LA), and presented to one ear using Sennheiser HD-25 headphones (Wedemark, Germany). Responses were recorded on a touch screen monitor (Mimo Magic Touch, Mimo Monitors, Princeton, NJ). All testing took place in a double-walled sound attenuated room.

D. Amplification

Stimuli were amplified for the participants with hearing loss using a hearing-aid simulator (McCreery *et al.*, 2013, 2014) implemented in MATLAB (2009b). The signal processing steps are shown in Fig. 3. The compression speed for the WDRC circuit was set to fast (1 ms attack time, 5 ms release time), medium (5 ms attack time, 50 ms release time), or slow (150 ms attack time, 1500 ms release time). The equation used to control the gain is described in Kates (2008),

$$d(n) = \begin{cases} \alpha d(n-1) + (1-\alpha)|x(n)|, & |x(n)| \geq d(n-1) \\ \beta d(n-1), & |x(n)| < d(n-1), \end{cases} \quad (1)$$

where n is the sampling time point, $x(n)$ is the acoustic input signal, α is a constant derived from the attack time, and β is a constant derived from the release time.¹ For $n = 1$,

$d(n) = |x(n)|$, otherwise the above equation applies. $d(n)$ is a peak detector and its value was used by the WDRC circuit to determine the gain that was applied to the input signal. When the level of the input signal was the same or increasing over time, the first line of Eq. (1) applied. In that case, a large amount of the input signal was mixed in with $d(n)$ and, consequently, $d(n)$ rose rapidly. Therefore, the gain is decreased quickly. When the level of the output signal was decreasing over time, the second line of Eq. (1) applied. In that case, $d(n)$ decayed at a constant rate. Minimum and maximum gains were 0 and 60 dB, respectively. Linear amplification was implemented below the compression threshold (CT).

Each participant's auditory thresholds in dB hearing level were converted to dB SPL, using a transform derived from measurements on a Knowles Electronic Manikin for Acoustic Research (KEMAR: G.R.A.S. Sound and Vibrations, Holte, Denmark). Thresholds in dB SPL were entered into the DSL program. The DSL program was used to generate the WDRC and output CTs, the target output levels for conversational speech, and maximum output. Targets were generated for both the adult and child versions of DSL. To describe the CTs and compression ratios, the CTs and compression ratios for the WDRC channels centered at 1.6 and 2.5 kHz were averaged for each participant. The CTs were the same for DSL child and adult. The mean CT was 39 dB SPL (sd: 5.8, range: 28–47 dB SPL). The mean compression ratio for DSL-adult was 1.6 (sd: 0.3, range: 1.2–2.0). The mean compression ratio for DSL-child was 2.1 (sd: 0.3, range: 1.6–2.7).

Output levels were estimated using a transfer function derived from Sennheiser HD-25-1 headphones attached to KEMAR and a sound level meter (Larson Davis System 824, Provo, UT). Using a MATLAB script, an iterative procedure was implemented that estimated the output levels and adjusted the hearing-aid gain to match DSL targets. Output levels were estimated for 1/3-octave bands (ANSI, 2004) for the “carrot passage” (Audioscan®, Dorchester, ON) reproduced at 60 dB SPL and were within a mean of 0.2 dB (1.9 sd) of target at 2 kHz (the frequency of the masker and target). The text for the carrot passage is in the Appendix. Maximum output was estimated using 90 dB SPL swept pure tones.

Figure 4 shows how the amplification affected the stimuli for a representative participant. Waveforms for both prescriptive procedures (top row: DSL-adult, bottom row: DSL-child), two time delays (10 ms, 80 ms) and two compression speeds (fast, slow) are displayed. The effect of medium-speed compression falls between those described here for fast and slow compression. For this example, the target was presented at 52 dB SPL. These panels illustrate three effects of amplification: First, amplitudes for the masker were higher with slow than with fast compression, especially at the masker onset. Second, the amplitudes of the masker and target were higher with DSL-child than DSL-adult, due to the higher output level prescribed by DSL-child. Last, amplitudes for the target were higher with fast than with slow compression, due to the faster release time with fast compression.

FIG. 3. Signal processing used for the hearing-aid simulator. AT = attack time, RT = release time, CR = compression ratio, CT = compression threshold, DSL = Desired Sensation Level, WDRC = wide-dynamic range compression.

E. Procedure

Participants sat in front of a touch-screen monitor. Forward-masked thresholds were estimated by adapting the level of the target using a three-interval forced-choice task with a two-down one-up rule (Levitt, 1971). The starting level was 70 dB SPL. Each block consisted of seven reversals. The step sizes for the first three reversals were 18, 9, and 6 dB. The remaining 4 reversals used a 3-dB step size; the average levels at these 4 reversals were taken as threshold. A trial consisted of 3 observation intervals separated by 300 ms. Each interval was marked by a separate button that lighted up on the touch-screen monitor for approximately 1 s. Subjects indicated the interval that they thought contained the target by pressing the appropriate button. Feedback was provided.

Subjects practiced by obtaining two threshold estimated with a 100-ms time delay. The prescriptive fitting method (DSL-adult, DSL-child) and compression speed (fast, medium, slow) were randomized for the practice. For the experimental task, thresholds were estimated twice for each prescriptive fitting method, compression speed, and time delay (0, 10, 80 ms and no masker). If the two threshold estimates for a condition differed by more than 6 dB, threshold was estimated a third time. Thresholds for each condition were averaged across all estimates. With one exception, the order of conditions was randomized. Thresholds without amplification for the listeners with SNHL were obtained last.

F. Analysis

The amount of masking was calculated by subtracting the threshold in quiet from the threshold in the presence of the masker. Because subtracting a constant to derive the amount of masking did not change the pattern of results, only forward-masked thresholds were analyzed statistically. An analysis of variance (ANOVA) was performed on the forward-masked thresholds for the participants with SNHL using compression speed (fast, medium, slow), prescriptive procedure (DSL-adult, DSL-child) and time delay (0, 10, 80 ms) as within-subject factors. Mauchly's Test of Sphericity was used. In cases where the assumption of sphericity was violated, the degrees of freedom were adjusted using the Greenhouse-Geisser correction. *Post hoc* analysis used Tukey's test for Honestly Significant Differences. Unaided thresholds for the listeners with SNHL were analyzed descriptively.

Thresholds for the two groups (NH and SNHL) were compared to determine which compression speed and prescriptive procedure minimized differences in forward-masked thresholds for participants with SNHL relative to participants with NH. Because of the mixed-level design (participants with SNHL received repeated measures but participants with NH did not) it was not appropriate to analyze the data with a repeated-measures ANOVA. Instead, a multivariate ANOVA was completed with time delay as a dependent variable and fixed factor of condition (DSL adult-slow, DSL adult-medium, DSL adult-fast, DSL child-slow, DSL child-medium, DSL child-fast). *Post hoc* comparisons were made

FIG. 4. Waveforms of stimuli after amplification for one participant. The masker level was fixed at 70 dB SPL. Target level was 52 dB SPL. Waveforms for DSL-adult and child are plotted in the top and bottom rows, respectively. Waveforms for time delays of 10 ms (left two columns) and 80 ms (right two columns) are shown. The compression speed (fast, slow) is indicated in each panel.

using Dunnett’s test (Field, 2005), which is a multiple comparison procedure that was used to compare each treatment (prescriptive procedure and compression speed) with a single control condition (participants with NH).

III. RESULTS

A. Forward-masked thresholds

Figure 5 depicts the forward-masked thresholds for the participants with SNHL using DSL-adult (left panels) and DSL-child (middle panels) prescriptive procedures. Unaided forward-masked thresholds are also plotted for the participants with NH and for four participants with SNHL (right panels). As expected, unaided thresholds for the participants with SNHL were higher than with amplification. Thresholds for the participants with SNHL decreased in level as the time delay increased [$F(1.4, 11.1) = 98.9, p < 0.001, \eta_p^2 = 0.925$]. Thresholds also decreased as the compression speed increased (slow: $M = 54$ dB, $sd = 9$; medium: $M = 48$ dB, $sd = 12$; fast: $M = 45$ dB, $sd = 12$), [$F(1.8, 16) = 57.5, p < 0.001, \eta_p^2 = 0.878$]. Thresholds were lower for DSL-child ($M = 45$ dB, $sd = 12$) than for DSL-adult ($M = 53$ dB, $sd = 10$), [$F(1, 8) = 32.5, p < 0.001, \eta_p^2 = 0.803$]. Prescriptive procedure did not interact significantly with time delay [$F(1.9, 20.8) = 1.317, p = 0.295, \eta_p^2 = 0.141$]. However, the two-way interactions of compression speed with prescriptive procedure [$F(1.6, 16) = 6.1, p < 0.019, \eta_p^2 = 0.432$] and

compression speed with time delay [$F(1.4, 10.9) = 21.7, p < 0.001, \eta_p^2 = 0.731$] were significant. These two-way interactions must be interpreted in light of the significant three-way interaction between prescriptive procedure, time delay, and compression speed [$F(2.7, 21.7) = 4.6, p = 0.014, \eta_p^2 = 0.365$]. Significant changes in threshold as a result of changes in either the compression speed or delay time occurred more frequently with DSL-child than DSL-adult. For DSL-child, thresholds were significantly lower with fast than slow compression (0, 10, 80 ms), with fast than medium compression (0 and 10 ms), and with medium than slow compression (80 ms). In contrast, for DSL-adult, thresholds were significantly lower with fast than slow compression (10 and 80 ms) and with fast than medium compression (80 ms). These findings suggest that forward-masked thresholds decrease with shorter compression speeds more when the normal dynamic range is well mapped to the impaired dynamic range (DSL-child) than when it is not (DSL-adult).

Unaided forward-masked thresholds for the participants with SNHL were markedly higher than those for the participants with NH. Forward-masked thresholds with amplification were compared to those for the participants with NH to determine the compression speed and prescriptive procedure that best approximated the forward-masked thresholds for the participants with NH. The multivariate effects of compression speed and prescriptive procedure on forward-masked thresholds were significant

FIG. 5. Forward-masked thresholds. Thresholds for DSL-adult and child are shown in the left and middle columns, respectively. Thresholds for slow, medium, and fast compression are shown in the top, middle, and bottom rows, respectively. Unaided thresholds for participants with SNHL and NH are shown in the right column. Error bars represent 1 sd. Error bars are not shown when the sd is smaller than the symbol.

[$F(18, 153.2) = 7.96, p < 0.001$, Wilks' $\lambda = 0.155, \eta_p^2 = 0.463$]. The multivariate effects of compression speed and prescriptive procedure were significant for each time delay [0 ms: $F(6, 56) = 4.7, p = 0.001, \eta_p^2 = 0.337$; 10 ms: $F(6, 56) = 17.5, p < 0.001, \eta_p^2 = 0.653$; 80 ms: $F(6, 56) = 25.7, p < 0.001, \eta_p^2 = 0.734$]. Dunnett's test was used to determine the conditions where forward-masked thresholds for listeners with SNHL differed significantly from the forward-masked thresholds for the participants with NH. The mean differences and statistics for the Dunnett's test are shown in Table I. At 0-ms time delay, forward-masked thresholds were not significantly different from those for the listeners with NH for DSL-adult fast, DSL-child medium, and DSL-child fast. For the remaining conditions the thresholds were significantly higher for the participants with SNHL than for the NH participants. At 10 ms time delay, differences were not significant only for DSL-child fast. Otherwise the forward-masked thresholds were significantly higher for the participants with SNHL than for the NH participants. At 80 ms time delay, all differences were significantly higher for the participants with SNHL than for the NH participants. This suggests that DSL-child with fast compression best approximated the NH forward-masked thresholds.

B. Amount of masking

The amount of masking was calculated for each participant and the results are shown in Fig. 6. The amount of

TABLE I. Outcome of Dunnett's test for forward-masked thresholds for each signal delay, prescriptive procedure, and compression speed. Comparison group is the participants with normal hearing. The mean difference was calculated between the mean forward-masked threshold for the participants with hearing loss and the participants with normal hearing.

Compression speed	Mean difference	Standard error	<i>p</i>
0 ms, DSL-Adult			
Slow	11.7	3.3	0.004
Medium	9.4	3.3	0.030
Fast	8.6	3.3	0.057
0 ms, DSL-Child			
Slow	9.0	3.3	0.040
Medium	5.4	3.3	0.396
Fast	-1.6	3.3	0.992
10 ms, DSL-Adult			
Slow	18.9	2.3	<0.001
Medium	15.3	2.3	<0.001
Fast	11.3	2.4	<0.001
10 ms, DSL-Child			
Slow	11.6	2.4	<0.001
Medium	8.6	2.4	0.003
Fast	0.8	2.4	0.999
80 ms, DSL-Adult			
Slow	26.8	2.6	<0.001
Medium	19.5	2.6	<0.001
Fast	19.7	2.6	<0.001
80 ms, DSL-Child			
Slow	22.9	2.6	<0.001
Medium	9.7	2.6	0.003
Fast	9.6	2.6	0.003

masking without amplification was less than that with amplification. As expected, the amount of masking decreased as the time delay increased. The amount of masking also decreased as the compression speed increased (slow: $M = 31$ dB, $sd = 10$; medium: $M = 25$ dB, $sd = 13$; fast: $M = 21$ dB, $sd = 11$) and when the prescribed gain decreased from DSL-child ($M = 28$ dB, $sd = 13$) to DSL-adult ($M = 24$ dB, $sd = 10$). Increasing the compression speed led to small decreases in masking at each time delay with DSL-adult. In contrast, increasing the compression speed led to large decreases in masking at each time delay with DSL-child.

The unaided amount of masking was less for the participants with SNHL than for those with NH. For DSL-adult, the amount of masking was greater than for the NH participants with slow compression at 80 ms time delay. However, the amount of masking was lower than for the NH participants with medium compression at 0 ms time delay and with fast compression at 0 and 10 ms time delays. For DSL-child, the amount of masking was less with slow compression at 80 ms time delay and with fast compression at 0 and 10 ms time delays. Notice that performance was most similar for the two groups when DSL-child with medium compression was used.

IV. DISCUSSION

The data support our hypothesis that both the prescriptive procedure and compression speed affect measures of forward masking. As expected, forward-masked thresholds and the amount of masking decreased with faster compression speeds. The decrease was larger with the procedure that better restored the dynamic range of hearing (DSL-child), and presumably also restored cochlear compression, than with the other procedure (DSL-adult). To approximate the performance of the listeners with NH, it was necessary to both restore the dynamic range of hearing (DSL-child) and use a fast compression speed. Forward-masked thresholds were higher without amplification than with amplification but the amount of masking was less without amplification. Neither DSL-child nor fast compression, by itself, resulted in the restoration of forward masking or amount of masking.

Medium compression with DSL-child best mimicked the amount of masking present for listeners with NH. This was surprising because it is generally agreed that compression in the cochlea is nearly instantaneous (Ruggero, 1992) and that this compression reduces forward masking (Oxenham and Plack, 2000). However, thresholds in quiet were higher for listeners with SNHL than for those with NH. This meant that, for the participants with SNHL, their threshold in quiet limited the amount of masking. The reason for higher than normal thresholds was because DSL does not attempt to restore the dynamic range of hearing for low-level inputs (Scollie *et al.*, 2005). It is possible that if the dynamic range of hearing had been fully restored, fast compression would have produced equivalent masking to that for the participants with NH.

The ability for the listeners with SNHL to detect the target signal might have been limited by other factors, such as

FIG. 6. Amount of masking, extracted from the data shown in Fig. 5. Otherwise as Fig. 5.

having greater neural adaptation, a longer period of neural recovery following the masker, or a longer temporal integrator. While the current data cannot determine if our listeners with SNHL had longer temporal integration, we do not think that this was the case. Auditory-temporal window models are similar for listeners with NH and SNHL (Moore *et al.*, 1989; Moore, 1993). In chinchillas with noise induced hearing loss, neural adaptation and recovery have been shown to be greater and longer, respectively, than with NH (Scheidt *et al.*, 2010) and this may have contributed to the present findings.

The findings that the prescriptive procedure and compression speed affect forward masking are consistent with previous research on forward masking. When differences in audibility are minimized between the two groups (NH and SNHL) disparities in forward masking are reduced (Kidd *et al.*, 1985; Schairer *et al.*, 2008). Desloge *et al.* (2011) demonstrated that mimicking the loss of audibility and cochlear compression in the impaired ear using listeners with NH reduced differences in forward masking relative to listeners with SNHL. Last, Johannesen *et al.* (2014) showed that the shallower slope of the forward-masking recovery function in listeners with SNHL than with NH could be attributed to the loss of the cochlear compression. This study builds on the previous research by demonstrating that by choosing a prescriptive fitting method and compression speed that better mimics the normal cochlear compression, one can restore forward masking for listeners with SNHL.

While previous studies have not examined the influence of the prescriptive procedure, other studies have also found that fast compression can result in similar measures of temporal resolution between listeners with SNHL and NH. Glasberg and Moore (1992) and Moore *et al.* (2001) noted that gap detection thresholds better approximated those for listeners with NH when the listeners with SNHL listened via fast (15 ms attack time, 30 ms release time) instead of slow (300 ms attack time, 3 s release time) compression. Brennan *et al.* (2013) found reduced detectability of amplitude modulation with fast than slow compression for listeners with SNHL. The latter finding may appear to refute the argument that fast compression best restores measures of temporal resolution. However, when tested at an equal SL, listeners with SNHL exhibit better modulation detection thresholds than listeners with NH (Bacon and Viemeister, 1985; Moore *et al.*, 1996; Moore and Glasberg, 2001). Because these listeners can show better detection of amplitude modulation (presumably due to the more linear function of the impaired cochlea) than those with NH, compressing the amplitude-modulated stimulus for listeners with SNHL may result in performance that is more similar to that of listeners with NH.

To date, one study conflicts with the argument that fast compression best restores normal temporal resolution. In a modulation-detection-interference task, Shen and Lentz (2010) found poorer thresholds with compression than without compression. They argued that compression altered across-frequency grouping cues, leading to the poorer than

normal performance. While compression might have altered grouping cues, in that study compression was only applied to the interferer and not to the target. Therefore, compression was not allowed to restore thresholds, as was done in this study. Thus, most studies to date have shown that the use of fast compression for listeners with SNHL results in measures of temporal resolution that better approximate the temporal resolution of listeners with NH.

Limitations of this study are worth noting. One limitation was the use of amplification with a hearing aid simulator. With real hearing aids, more variability in audibility across individual listeners is expected, due to a variety of factors. Limits in hearing-aid gain could restrict audibility. Acoustic feedback may preclude the use of higher gain. Gain might be reduced to address individual listener preference (e.g., Smeds, 2004). This study only examined one measure of temporal resolution at a single frequency and masker level. Future work is necessary to describe conditions in which temporal resolution can be restored for listeners with SNHL.

V. CONCLUSIONS

This study measured forward masking with compression amplification. Better mapping of the normal dynamic range to the impaired dynamic range with hearing-aid compression steepened the recovery function of forward masking (i.e., made the maskers less effective for longer than shorter temporal gaps). While using a faster compression speed improved both forward-masked thresholds and decreased the amount of masking, this effect was stronger when the input dynamic range was larger (DSL-child) than smaller (DSL-adult). The DSL-child prescriptive procedure with fast compression best restored forward-masked thresholds. These findings suggest, as argued by others, that SNHL does not cause a reduction in temporal resolution central to the cochlea but instead it is the loss of the cochlear compression that contributes to differences in forward masking between listeners with NH and SNHL. This is an initial evaluation of forward masking under amplification. These results should be verified for a wider range of stimulus frequencies and masker levels. Additional measures should be made with other methods of fitting amplification (e.g., Keidser *et al.*, 2011).

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APPENDIX

Carrot passage: A carrot is a long reddish yellow vegetable which has several thin leaves on a long stem and which belongs to the parsley family. Carrots are grown all over the world in gardens and in the wild in the fields.

¹ α was 9.0928, 45.4639, and 1363.9 for attack times of 1, 5, and 150 ms, respectively. β was 61.8687, 618.6869, and 18 561 for release times of 5, 50, and 1500 ms, respectively.

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