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Research Article

Masking Release in Children and Adults With Hearing Loss When Using Amplification

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Purpose: This study compared masking release for adults and children with normal hearing and hearing loss. For the participants with hearing loss, masking release using simulated hearing aid amplification with 2 different compression speeds (slow, fast) was compared.
Method: Sentence recognition in unmodulated noise was compared with recognition in modulated noise (masking release). Recognition was measured for participants with hearing loss using individualized amplification via the hearing-aid simulator.
Results: Adults with hearing loss showed greater masking release than the children with hearing loss. Average masking release was small (1 dB) and did not depend on hearing status. Masking release was comparable for slow and fast compression.
Conclusions: The use of amplification in this study contrasts with previous studies that did not use amplification. The results suggest that when differences in audibility are reduced, participants with hearing loss may be able to take advantage of dips in the noise levels, similar to participants with normal hearing. Although children required a more favorable signal-to-noise ratio than adults for both unmodulated and modulated noise, masking release was not statistically different. However, the ability to detect a difference may have been limited by the small amount of masking release observed.

This study examined the effects of hearing-aid compression speed and age (children vs. adults) on masking release. Masking release is a measure of the ability to use dips in a background noise to enhance speech recognition (e.g., Bacon, Opie, & Montoya, 1998). It is often quantified by comparing recognition of speech in unmodulated noise to that in amplitude-modulated noise. Adults with normal hearing show better recognition of speech in modulated noise than in unmodulated noise (e.g., Jin & Nelson, 2010), providing evidence that they can use speech information in the dips of the noise (Brungart, Simpson, Ericson, & Scott, 2001). For reviews of other mechanisms that might contribute to listening in the dips, see Stone and Moore (2014) and Füllgrabe, Berthommier, and Lorenzi (2006). Adults with sensorineural hearing loss almost always show less masking release than adults with normal hearing, and children show less masking release than adults (Bernstein & Grant, 2009; Hall, Buss, Grose, & Roush, 2012; Jin & Nelson, 2010; Lorenzi, Husson, Ardoint, & Debruille, 2006; Peters, Moore, & Baer, 1998; Summers & Molis, 2004). Reasons for these differences between groups with and without hearing loss are not clear. However, a review of the literature suggests that a difference in audibility between groups may be a contributing factor.

Hearing Status

Although the effect of audibility on masking release can be demonstrated by simulating hearing loss in participants with normal hearing (Bacon et al., 1998; Desloge, Reed, Braida, Perez, & Delhorne, 2010; Gregan, Nelson, & Oxenham, 2013), this does not indicate the extent to which amplification restores masking release for participants with hearing loss. Many studies that compared participants with hearing loss to participants with normal hearing (Bernstein & Grant, 2009; Hall et al., 2012; Lorenzi et al., 2006; Summers & Molis, 2004) did not apply frequency-shaped amplification. Therefore, parts of the signal may not have been audible for some frequencies during the dips in the masker level. Three studies that did apply frequency-shaped amplification found that adults with hearing loss showed less masking release than participants with normal hearing (George, Festen, & Houtgast, 2006; Jin & Nelson,

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2006; Peters et al., 1998). However, the amplification used in those studies was linear. This means that speech during dips in the noise level received the same amount of gain as the more intense parts of speech. In contrast, because wide dynamic range compression (WDRC) increases gain for low-level inputs, better audibility can be provided for speech during dips in the noise level. As a result, greater masking release might be expected to occur with WDRC than with linear amplification. On the other hand, improved audibility may (Plomp, 1988) or may not (Villchur, 1989) be offset by increased temporal distortion or comodulation of speech with the masker, especially when the masker is competing speech (Stone & Moore, 2007, 2008), resulting in similar or even less masking release.

Although the effect of WDRC amplification on masking release has not been studied in detail, the influence of WDRC on speech recognition in modulated noise has been examined for adults (Moore, Peters, & Stone, 1999; Souza, Boike, Witherell, & Tremblay, 2007). Moore et al. (1999) concluded that WDRC improved the speech-recognition threshold for speech in modulated noise by 0.5 to 0.9 dB compared with linear amplification. In contrast, Souza et al. (2007) found poorer speech recognition scores for modulated noise with WDRC than with linear amplification. Distortion of temporal cues and/or comodulation of the speech with the noise could explain why speech recognition was poorer with WDRC in the Souza et al. study but cannot account for why recognition was better in the Moore et al. (1999) study. The speech presentation level or type of maskers used could explain the differing results. Moore et al. generally used lower speech levels than Souza et al., which may have been beneficial because WDRC results in better audibility than linear amplification for low-level speech. The envelope of 12 talkers modulated the noise used in Souza et al., whereas the envelope of a single talker modulated the noise used by Moore et al. The envelope of a 12-talker masker has limited modulation depth, which is expected to result in less release from masking, even for participants with normal hearing (Bronkhorst & Plomp, 1992; Strelcyk & Dau, 2009; for a review, see Bronkhorst, 2000).

Compression Speed

The degree to which WDRC can overcome the negative effects of hearing loss on masking release may also be influenced by compression speed (Alexander & Masterson, 2015). *Compression speed* refers to the rate at which a hearing aid adjusts gain in response to changes in input level. Gain during dips in the masker level will increase more rapidly with fast WDRC (release time < 100 ms) than with slow WDRC (release time ≥ 100 ms). The greater gain with fast WDRC is expected to lead to increased audibility of the speech, and, as a consequence, masking release should improve. To the extent that random amplitude fluctuations in the masker impede speech understanding, fast WDRC might improve masking release by minimizing these envelope fluctuations (Glasberg & Moore, 1992; Stone & Moore, 1992). Again, this benefit could come at a cost of increased distortion of speech with fast WDRC (Plomp, 1988; but see Villchur, 1989). Alexander and Masterson (2015) examined the influence of the number of compression channels and of slow and fast release times for WDRC on the perception of speech in unmodulated noise and modulated noise for adults with hearing loss. At a fixed 0-dB signal-to-noise ratio (SNR), greater masking release was observed with fast than with slow release times.

Age

Children may be less able than adults to benefit from dips in the masker. Children with normal hearing require a more favorable SNR for speech understanding than adults with normal hearing for both unmodulated and modulated noise (Hall et al., 2012; McCreery & Stelmachowicz, 2011). Children with normal hearing also show less masking release than adults with normal hearing (Hall et al., 2012; Stuart, 2005; Wróblewski, Lewis, Valente, & Stelmachowicz, 2012). Children with hearing loss have reduced access to speech (due to their hearing loss) and are still developing the ability to recognize speech. Although adults with adult-onset hearing loss have a similar reduction in access to the speech signal, adults already have a robust system in place for understanding speech. This robust system may allow them to benefit more from a modulated masker than children because adults might better be able to use the additional information provided during dips in the masker level. Therefore, children with hearing loss might exhibit less masking release than adults with hearing loss. Hall et al. (2012) measured masking release for sentences using children and adults with normal hearing and hearing loss. The sentences were presented at the same level—86 dBA—for all participants. No frequency-shaped amplification was provided for the participants with hearing loss. They found that both adults and children with hearing loss demonstrated less masking release than their peers with normal hearing. It is interesting to note that there was no difference in masking release between the children and adults with hearing loss, whereas the children with normal hearing had less masking release than the adults with normal hearing. Because frequency-shaped amplification was not used, the differences in outcomes between the two groups (normal hearing, hearing loss) could have been due to differences in audibility rather than differences in their ability to use the speech cues present during the dips in the masker level.

SNR

An additional factor that has been shown to influence the magnitude of masking release is the SNR of the unmodulated noise at which the comparison with modulated noise is made. Greater masking release has been observed when the percentage correct is not near floor or ceiling and when the SNR is negative (Alexander & Masterson, 2015; Bernstein & Grant, 2009; Oxenham & Simonson, 2009). However, there is disagreement regarding the influence of the unmodulated noise SNR on masking release. Hall et al. (2012) measured masking release at two different percentage correct values (and hence SNRs) for adults with normal hearing and did not find that masking release differed across SNRs. Regardless, it is still useful to know the SNR that is required for children with hearing loss to achieve criterion speech recognition and how their masking release compares with that of their peers with normal hearing and that of adults with normal hearing or hearing loss.

The present study tested the effects of hearing loss and age on masking release. Adults and children were included to test the hypothesis that masking release would be smaller for children than for adults. Participants with normal hearing and hearing loss were included to test the hypothesis that improving audibility for participants with hearing loss would result in a similar amount of masking release between groups. To test the hypothesis that masking release would be greater with fast than with slow WDRC for both age groups (children, adults), the participants with hearing loss were tested using simulated hearing aids with two compression speeds.

Method

Participants

Twenty-one children with normal hearing (14 girls, seven boys; median = 10 years, range = 6–16 years, *M* = 10 years, *SD* = 3), 17 children with hearing loss (six girls, 11 boys; median = 11 years, range = 7–16 years, *M* = 11 years, *SD* = 3), 19 adults with normal hearing (18 women, one man; median = 51 years, range = 21–65 years, *M* = 45 years, *SD* = 17), and 17 adults with hearing loss (11 women, six men; median = 55 years; range = 19–68 years, *M* = 47 years, *SD* = 19) participated in this study.[1] Each adult with normal hearing was age matched within 5 years to an adult with hearing loss. Each child with normal hearing was age matched within 6 months to a child with hearing loss. Eleven of the children were 13 to 16 years of age, and 27 children were younger than 13 years.

Participants were not matched on other characteristics (e.g., socioeconomic status). All of the children (normal hearing, hearing loss) were in mainstream classes or were home schooled and used spoken English without sign support. Participants were recruited from the Human Research Subjects Core database at Boys Town National Research Hospital. Informed consent and assent were obtained for all participants according to the procedures required by the Institutional Review Board at Boys Town National Research Hospital. Participants were compensated $15 per hour.

Of the children with hearing loss, all wore bilateral WDRC hearing aids. Four children used Phonak (Warrenville, IL) nonlinear frequency compression. Of the adults with hearing loss, 10 wore bilateral WDRC hearing aids; four of those used Phonak nonlinear frequency compression.

For both children and adults, *normal hearing* was defined as pure-tone thresholds ≤ 25 dB HL from 0.25 to 8.00 kHz, bilaterally. Hearing thresholds were obtained for 13 of the 19 adults with normal hearing and for six of the 21 children with normal hearing. To save time, the remaining participants (six adults, 15 children) were screened for normal hearing at 15 dB HL. Mean ear-specific audiometric thresholds for the participants with hearing loss are shown in Figure 1. For the experimental conditions, all participants completed the experiments with bilateral amplification of stimuli. The participants with hearing loss had a difference in the pure-tone average at 0.5, 1.0, and 2.0 kHz of less than 15 dB between ears, except for one child and one adult who had differences of 23 and 16 dB, respectively.

Stimulus Material

Test stimuli were developed that minimized predictability on the basis of context and emphasized bottom-up processing of acoustic information but contained words that were familiar to all age groups. Test stimuli were randomly selected from a pool of 328 low-predictability sentences. These sentences were syntactically correct but semantically anomalous. Candidate words were derived from the following lists: Bamford-Kowal-Bench Sentence Lists (Bench, Kowal, & Bamford, 1979), Computer Aided Speech Perception Assessment 5.0 (Boothroyd, 2006), California Consonant Test (Owens & Schubert, 1977), Hearing in Noise Test for Children (Nilsson, Soli, & Gelnett, 1996), Modified Rhyme Test (House, Williams, Hecker, & Kryter, 1965), Northwestern University Children's Perception of Speech (Elliott & Katz, 1980), Phonetically Balanced Kindergarten Word Lists (Haskins, 1949), and the Word Intelligibility by Picture Identification Test (Ross & Lerman, 1971). Each word was entered into the Child Corpus Calculator (Storkel & Hoover, 2010), and words not in the child lexicon were removed. From these words, 1,730 words were retained. Next, each possible part of speech (verb, noun, adjective, adverb, pronoun) was determined for every word. A MATLAB script was used to randomly generate sentences. Each sentence followed one of nine sentence structures using four key words (e.g., adjective, noun, verb, noun; see Table 1). Articles were then added to each sentence to make it grammatically correct. Two audiologists judged each sentence as being semantically meaningful or not meaningful and syntactically correct or incorrect. For any disagreement, a third audiologist examined that sentence and made the final judgment. Sentences that were semantically meaningful or not syntactically correct were removed, or the words were recombined to produce new low-predictability sentences. Table 1 contains example sentences.

A native English-speaking female with a Midwest accent recorded the sentences in a double-walled, sound-treated room. The talker spoke the sentences at a conversational level and rate into a condenser microphone (Shure

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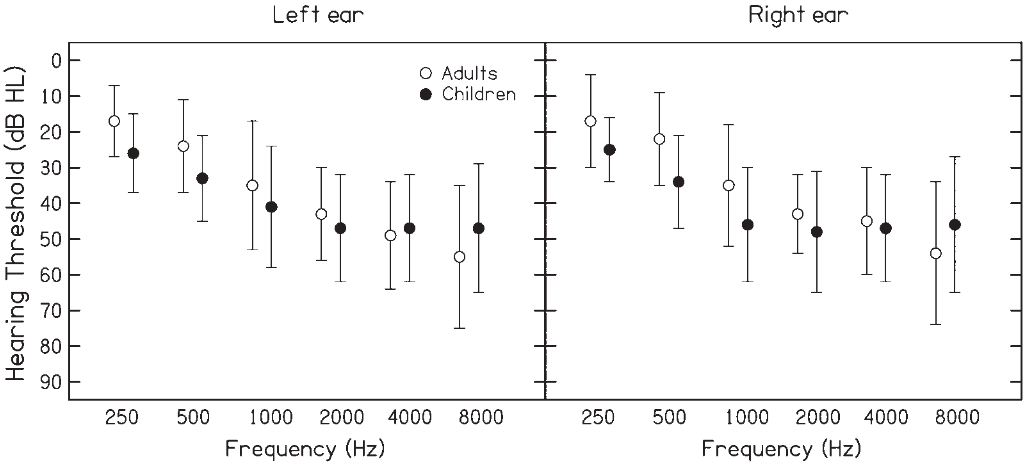
[1] Six participants (four children with hearing loss and two adults with hearing loss) were excluded because they required a high SNR (>20 dB SNR) for at least one condition. Electroacoustic analysis showed that the noise was inaudible for these listeners when the SNR was greater than 20 dB.

Figure 1. Mean hearing thresholds for left ear (left panel) and right ear (right panel) for adults (unfilled) and children (filled) with hearing loss. Error bars represent ±1 *SD*.



Beta 53, Niles, IL) that was placed approximately 2 in. from her mouth. The recorded signal was routed to a preamplifier (Shure M267) and digitized (Lynx TWO-B, Costa Mesa, CA) at a sampling rate of 44.1 kHz (32 bits). Two exemplars of each sentence were recorded. A rater selected the best production of each sentence on the basis of clarity. As a final check, three adults with normal hearing listened to each sentence in quiet at 60 dB SPL, and any sentences for which two or more participants repeated a word incorrectly were discarded. Twenty sentences were excluded using this procedure. The final sentences had a mean duration of 2.4 s (range = 1.6–4.7 s).

Two noise maskers—unmodulated and modulated—were used. Both types were spectrally matched to the international long-term average speech spectrum as reported by Byrne et al. (1994) for the combined male and female talkers (see their Table 2). Fifty noise samples for each type were created and were randomly drawn for stimulus presentation. The unmodulated masker was continuous noise. The modulated masker was signal-correlated-noise derived from two female talkers (different talkers than those used to record the test stimuli) who spoke the “rainbow” passage (Fairbanks, 1960, p. 172) at a conversational level and rate. Pauses in each passage were not removed. An advantage of using two talkers is that the masker has an envelope more likely to be encountered outside of the laboratory than that of a square-wave or sinusoidal modulator, as is sometimes used for studies on masking release (e.g., Hall et al., 2012). The passage was recorded in the same manner as described for the sentences. The recordings from the two talkers were equated in root-mean-square level. Fifty random time slices, 5.5 s in duration, were extracted from each passage. The two talkers’ samples from each time slice were summed together. The sample point for each time slice was randomly multiplied by +1 or −1 to create 50 signal-correlated-noise samples. This procedure preserved the temporal envelope of the original signal but with a noisy, flat spectrum that was then spectrally matched to the long-term average speech spectrum. The noise was combined with the speech prior to presentation and started 400 ms before and extended 400 ms after the sentence. The noise was gated on and off with 10-ms cosine-squared functions. Prior to being combined with the sentences, the two types of noise were equated in average root-mean-square level and, consequently, were not equated in peak level.

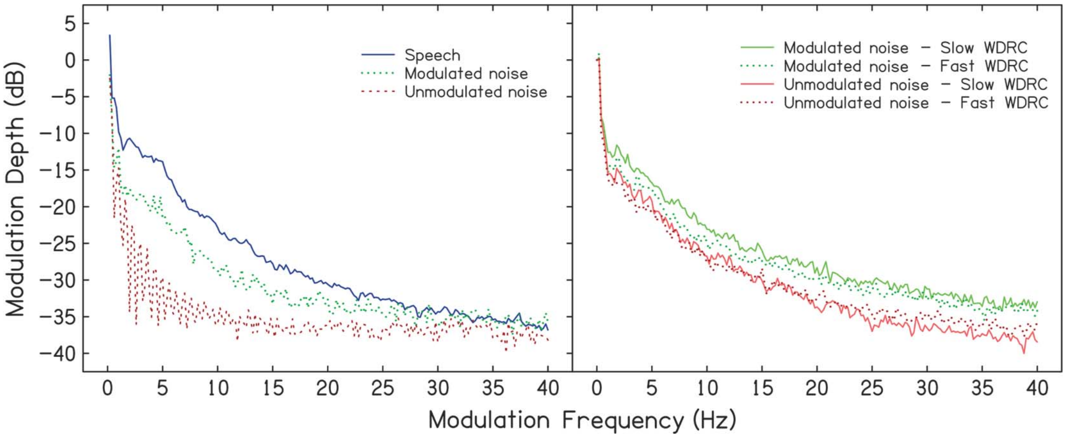
Table 1. Example sentences.

Example sentence	Parts of speech
The **cloudy skateboard split often**.	Adjective, noun, verb, adverb
The **show disappeared four wagons**.	Noun, verb, adjective, noun
I **sold myself** to the **closet nut**.	Verb, pronoun, noun, noun
The **invisible bells did** that **together**.	Adjective, noun, verb, adverb
Even tennis can **mow** the **smell**.	Adverb, noun, verb, noun
I **set** the **foam without** the **cow**.	Verb, noun, preposition, noun
Underwear wonders toward the **zebra**.	Noun, verb, preposition, noun
The **noisy screw** had **come** to **spray**.	Adjective, noun, verb, verb
My throw is **what** brings **peace**.	Pronoun, verb, pronoun, noun

Note. Pronouns included indefinite pronouns. Key words shown in bold.

The modulation spectra of the speech and two types of noise stimuli were computed using a method described in Gallun and Souza (2008). The stimuli were half-wave rectified, low-pass filtered at 50 Hz, down-sampled to 1000 Hz (for computational efficiency), and then submitted to a fast Fourier transform. The normalized modulation depth was computed for each fast Fourier transform by computing the energy in that bin and then dividing by the

Figure 2. (a) Modulation spectrum of speech (blue line), modulated noise (green line), and unmodulated noise (red line). Higher numbers indicate greater modulation depth. (b) Modulation spectrum of combined speech and noise following slow and fast wide dynamic range compression (WDRC). As expected, the modulation depth was greater for slow than fast compression and for continuous than modulated noise.



energy in the 0-Hz bin. The normalized modulation depths were averaged over each stimulus set (sentences, unmodulated noise, modulated noise) and are plotted in Figure 2, (panel a). The modulation depth increased, as expected, in order: unmodulated noise, modulated noise, and speech.

Amplification

Sentence and noise stimuli were processed with a hearing-aid simulator (Alexander & Masterson, 2015; Brennan et al., 2014; McCreery, Brennan, Hoover, Kopun, & Stelmachowicz, 2013), implemented using MATLAB (R2009b), in order to have more control over the compression parameters than is possible with a typical hearing aid. The stages in the program included an input limiter, filterbank, WDRC, and output limiter. The input limiter used a 1-ms attack time, 50-ms release time, 10:1 compression ratio, and 105-dB SPL compression threshold. The filterbank consisted of the following eight overlapping channels with center frequencies and, in parentheses, cutoff frequencies (−3 dB): 0.25 (0, 0.3), 0.4 (0.33, 0.5), 0.63 (0.52, 0.74), 1 (0.85, 1.16), 1.6 (1.31, 1.92), 2.5 (2.07, 3.09), 4 (3.24, 4.95), and 6.3 (5.10, 11.025) kHz. The WDRC circuit had two compression speeds: fast (5-ms attack time, 50-ms release time) and slow (150-ms attack time, 1500-ms release time). The compression speeds were chosen because it was desired that fast compression would better follow the dips in the masker level than slow compression and to maintain a 10:1 ratio between the attack and release times. The output limiter used the same compression settings as the input limiter circuit except that the compression thresholds were prescribed by the Desired Sensation Level Algorithm (DSL 5.0a; Scollie et al., 2005), as described later. All compression characteristics are referenced to the ANSI (2009) standard. Gain control circuits were implemented using Equation 8.1 of Kates (2008):

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

where n is the sampling time point, $\chi(n)$ is the input signal, $d(n)$ is the gain control signal, α is a constant derived from the attack time, and β is a constant derived from the release time. For $n = 1$, $d(n) = /x(n)/$; otherwise, the above equation applied. Gain was determined by computing the difference between the input and the desired output, where the input was $d(n)$. The minimum gain was limited to 0 dB, and the maximum gain was limited to 65 dB. Because the simulator used a 22050-Hz sampling rate, all stimuli were downsampled, which limited the upper bandwidth of amplification to 11025 Hz.[2]

For each participant, DSL was used to prescribe the gain, compression threshold, compression ratio, and maximum output parameters of the simulator. Targets were generated individually for each ear. Age-appropriate prescription targets were used for the two age groups (Scollie et al., 2005) and were lower for adults than for

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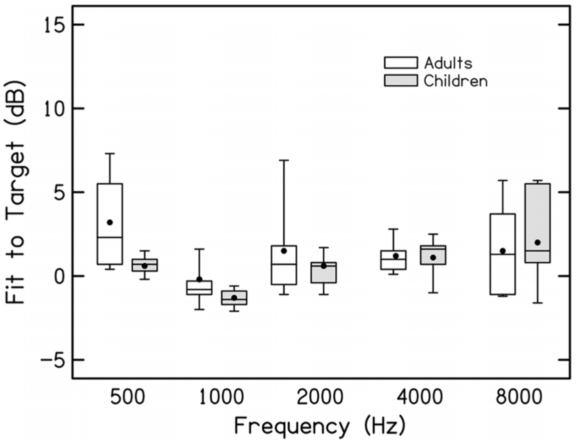
[2] It is conceivable that differences in audibility above the highest frequency tested for hearing (8 kHz) may have had a small effect on the results. This is because the highest center frequency used by the speech intelligibility index (ANSI S3.5-1997) is 8.5 kHz (critical band method), and the importance function at 8.5 kHz (.0110) is the second-lowest band importance function. Moore, Füllgrabe, and Stone (2010) found that the mean score improved by 5 and 3 RAU, which corresponds to 5% and 3% (see Studebaker, 1985), when a low-pass filter cutoff frequency was increased from 7.5 to 10.0 kHz for their listeners with and without hearing loss, respectively (see their Figures 5 and 6). On the basis of the performance-intensity functions for the present study (see Figure 6), a decrement of 5% and 3% could have reduced performance for both noise types (modulated, unmodulated) by 0.8 and 0.6 dB SNR. These differences would not change the conclusion that masking release was similar for the two groups (NH, HL).

children. The binaural correction (−3 dB) was not applied for either group. Thresholds in hearing level were converted to sound pressure level using conversion factors for a Knowles Electronic Manikin for Acoustic Research (G.R.A.S. Sound & Vibrations, Holte, Denmark), and the thresholds were subsequently entered into the DSL program. Because DSL does not provide a target sensation level at 8000 Hz, the target sensation level at 8000 Hz was the same as that at 6000 Hz. To prevent a sharp change in the frequency response, the resultant sensation level was limited to the target sensation level at 6 kHz plus 10 dB.

The output levels were estimated for Sennheiser HD-25 (Wedemark, Germany) headphones attached to a Knowles Electronic Manikin for Acoustic Research with an IEC 711 coupler for each participant. The simulator automatically adjusted gain to match the prescribed DSL targets for a 60-dB SPL speech input level and the limits for maximum output using a 90-dB SPL swept pure tone. The speech used for gain adjustment consisted of the "carrot" passage from the Verifit (Audioscan, Dorchester, Ontario, Canada) hearing-aid analyzer. This generally resulted in output levels based on one-third octave filters (ANSI S1.11-2004) that were within 5 dB of the DSL targets, as shown in Figure 3.

The modulation spectrum of the amplified speech and the two types of noise was computed as described above. The normalized modulation depths were averaged over each stimulus set (sentences, unmodulated noise, modulated noise) and participant and are plotted in Figure 2 (panel b). The modulation depth was lower for fast than for slow WDRC with modulated noise. In contrast, the modulation depth was similar for fast and slow WDRC with unmodulated noise.

Figure 3. Fit to target showing the difference (in dB) between the root-mean-square (RMS) sound pressure level with the simulated hearing aid for the "carrot" passage and the target sound pressure level for the adults (unfilled) and children (filled). The upper and lower margins of the boxes represent the interquartile range, and the upper and lower margins of the whiskers represent the 10th and 90th percentiles, respectively. For each box, the line within the box represents the median and the filled circles represent the mean.



Procedure

Participants were seated in a sound-attenuating booth. Stimulus presentation and data collection were controlled using a personal computer and custom MATLAB (2009b) scripts. The order of conditions and sentence presentations was randomized. For the participants with hearing loss, stimuli were presented bilaterally with amplification individualized for each ear. Each sentence was presented at 60 dB SPL to the input of the hearing-aid simulator. For the participants with normal hearing, each sentence was presented bilaterally at 60 dB SPL without amplification.

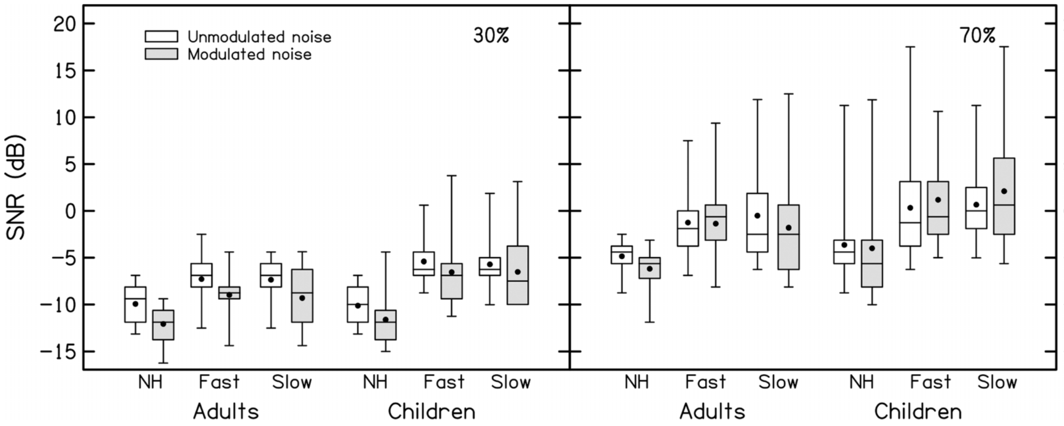
An interleaved, two-track, adaptive procedure (Levitt, 1971) was used to vary the noise level to measure the 30% (one down, two up) and 70% (two down, one up) performance points on the performance-intensity function. The starting SNR was 10 and 20 dB for the 30% and 70% performance points, respectively. Six reversals were obtained for each track. In the event that one track was completed before the other track, data collection was discontinued for the completed track. Data collection continued for the remaining track until the stopping rule was reached for that track. The step size up to the first two reversals was 10 dB, and the step size for the remaining four reversals was 5 dB. The final step size was based on pilot data, which showed equivalent thresholds for 3- and 5-dB step sizes. The combined speech and noise were presented to the input of the hearing-aid simulator, with digital-to-analog conversion of the amplified stimuli provided by a Lynx Studio Technology Two B sound card (Costa Mesa, CA). The sentences plus the noise were routed via a MiniMon Mon800 monitor matrix mixer (Behringer, Kirchardt, Germany), amplified with a PreSonus HP4 headphone distribution amplifier (Baton Rouge, LA), and presented bilaterally using Sennheiser HD-25 headphones. Participants completed one practice run with the modulated and unmodulated noise followed by two threshold estimates per condition. The mean of the two threshold estimates, on the basis of the last four reversals, was computed as threshold.

Participants were instructed to repeat back as much of each sentence as they could. A sentence was scored as correct if the participant correctly repeated at least 75% of the key words (three or four correct key words). Picture rewards were displayed after each response on a monitor for the younger children and were used to maintain their attention on the task. The pictures consisted of various animals and scenery and were unrelated to the sentences. Adults and older children had the option to turn off the visual rewards.

Results

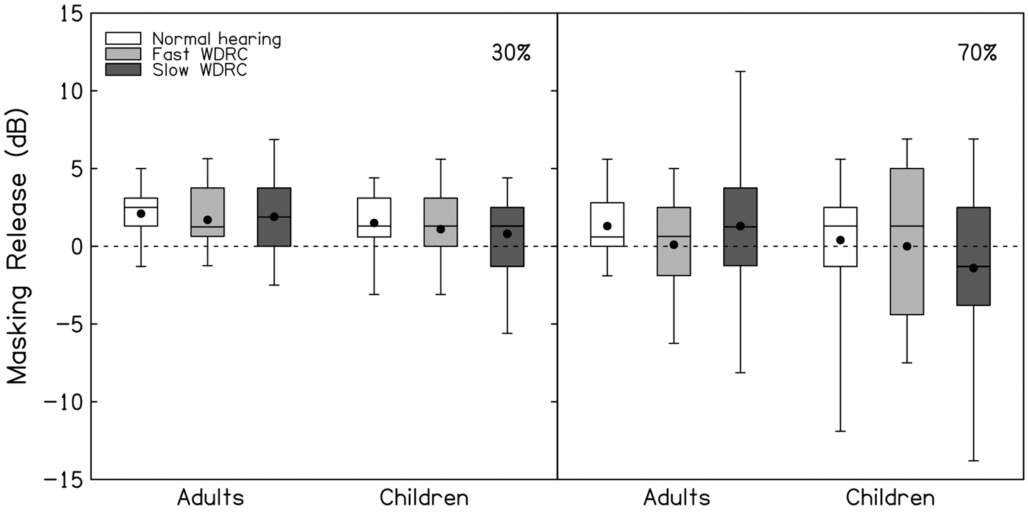
The SNRs required for 30% and 70% correct sentence recognition are plotted in Figure 4. Lower numbers indicate better performance. Masking release is indicated when the SNR is lower for the modulated than the unmodulated noise. Masking release is plotted in Figure 5, with positive values indicative of masking release.

Figure 4. Signal-to-noise ratio (SNR; in dB) for unmodulated noise (unfilled) and modulated noise (filled) for participants with normal hearing (NH) and those with hearing loss using fast and slow wide dynamic range compression. SNR for 30% correct is shown in the left panel, and SNR for 70% correct is shown in the right panel. Boxes represent the interquartile range, and whiskers represent the 10th and 90th percentiles. For each box, lines represent the median and filled circles represent the mean SNR.



To determine the effect of age and hearing loss on masking release, the data were analyzed using a mixed-model analysis of variance (ANOVA) with within-subject factors of performance-intensity point (30%, 70%) and noise type (unmodulated, modulated) and between-subjects factors of age group (children, adults) and hearing status (normal hearing, hearing loss). Because fast WDRC was hypothesized to result in a lower SNR and greater masking release, the data for fast WDRC were used for the participants with hearing loss. Past studies typically quantified masking release as the difference in SNR between the unmodulated masker condition and the modulated masker condition and then performed statistical analysis on the amount of masking release (e.g., Hall et al., 2012). This study, instead, examined the main effect of the noise condition and its interaction with the other conditions. A significant main effect of noise condition with a lower SNR for modulated than unmodulated noise would show that the participants demonstrated masking release on average. Any interactions with noise condition would indicate that the average amount of masking release differed by age or hearing status. Post hoc analysis was completed using paired-samples *t* tests with Bonferroni-Holm correction for multiple comparisons. This analysis avoided some commonly noted statistical problems that can occur when difference scores are analyzed (Edwards, 2001).

Figure 5. Masking release (in dB) for adults and children for 30% correct (left panel) and 70% correct (right panel). The upper and lower margins of the boxes represent the interquartile range, and the upper and lower margins of the whiskers represent the 10th and 90th percentiles, respectively. For each box, the line within the box represents the median and the filled circles represent the mean. WDRC = wide dynamic range compression.



Age

ANOVA results are shown in Table 2. The SNR was significantly lower for modulated noise (*M* = −6.4, *SD* = 5.6) than for unmodulated noise (*M* = −5.4, *SD* = 4.8), confirming that participants as a whole showed a release from masking. The noise condition did not interact significantly with age. As shown in Figure 5, masking release was similar for the two age groups. However, there was a significant effect of age (see Figure 4), with adults (*M* = −6.6, *SD* = 5.8) having a lower SNR than children (*M* = −5.2, *SD* = 5.8). The noise condition interacted significantly with the performance-intensity point because masking release occurred at the 30% (p = .001) but not the 70% (p < .294) performance-intensity point (see Figure 5). The three-way interaction of age, noise condition, and performance-intensity point was not significant. In addition, the bivariate correlation of age with masking release (unmodulated noise minus modulated noise) was not significant for the children (30%: r = .26, p = .11; 70%: r = −.06, p = .71). These findings show that although the SNR for unmodulated and modulated noise was lower for adults than for children, masking release was not statistically different.

Hearing Status

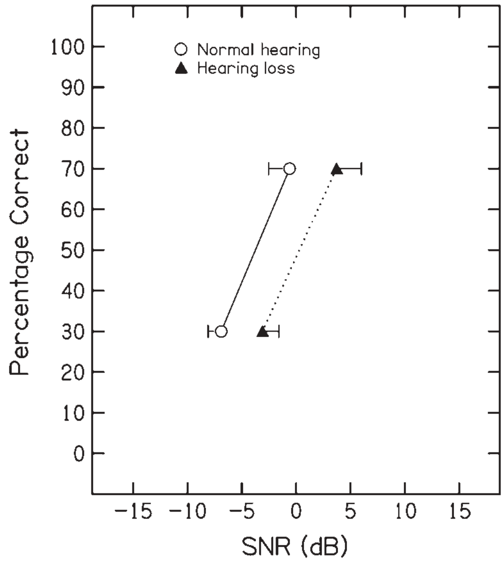
The effect of hearing status was significant. Participants with normal hearing had a lower SNR (*M* = −7.8, *SD* = 4.5) than participants with hearing loss (*M* = −3.7, *SD* = 5.4), as illustrated in Figure 6. Hearing status did not interact significantly with noise condition, indicating that masking release was not statistically different for the participants with normal hearing and those with hearing loss. There was not a significant interaction of the performance-intensity point with hearing status, as shown in Figure 6. The three-way interaction of hearing status, age, and noise condition was not significant. The three-way interaction of hearing status, noise condition, and performance-intensity point was also not significant, suggesting that there was not a statistical difference in masking release for the two groups (normal hearing, hearing loss) at either performance-intensity point. These findings demonstrated that although the participants with hearing loss required a more favorable SNR than the participants with normal hearing, masking release was not statistically different across groups.

Table 2. Analysis of variance for the listeners with normal hearing and hearing loss.

Main effects and interactions	*df*	*F*	*p*	η_p^2
Noise	1, 70	12.133	**.001**	.148
Age	1, 70	5.402	**.023**	.072
Hearing	1, 70	40.351	**< .001**	.366
PI	1, 70	440.561	**< .001**	.863
Age × PI	1, 70	1.395	.242	.020
Age × Noise	1, 70	2.181	.144	.030
Age × Hearing	1, 70	0.828	.366	.012
Age × Noise × PI	1, 70	0.139	.710	.002
Noise × PI	1, 70	7.530	**.008**	.097
Hearing × Noise	1, 70	2.304	.134	.032
Hearing × Age × Noise	1, 70	0.004	.950	< .001
Hearing × Noise × PI	1, 70	0.678	.413	.010
Hearing × Age × PI	1, 70	1.766	.188	.025
Hearing × PI	1, 70	0.648	.424	.009
Hearing × Age × PI × Noise	1, 70	0.001	.975	< .001

Note. PI = performance-intensity point. Bold values indicate p < .05.

Figure 6. Signal-to-noise ratio (SNR) for 30% and 70% correct for participants with normal hearing and participants with hearing loss (fast wide dynamic range compression) averaged across noise types. Includes both adults and children. Error bars represent 1 *SD*. Single instead of double error bars are shown to prevent overlap of the error bars.



Compression Speed

To determine the influence of compression speed on masking release, the data from the participants with hearing loss were analyzed separately using an ANOVA (see Table 3). The within-subject factors were performance-intensity point, compression speed, and noise type, and the between-subjects factor was age. The effect of compression speed was not significant, suggesting that the overall SNR was not statistically different for slow and fast WDRC, as also shown in Figure 7. Compression speed did not interact significantly with noise condition, demonstrating that masking release was not statistically different for slow and fast WDRC, as shown in Figure 5. Compression speed did not interact significantly with the performance-intensity point. The performance-intensity point interacted significantly with noise type due to masking release occurring for the 30% (p < .001) but not the 70% (p = .878) performance-intensity point. The noise type interacted significantly with age due to adults (p = .006) but not children (p = .884) showing masking release. None of the other two-, three-, or four-way interactions were significant. These findings show that masking release occurred for the 30% but not the 70%

Table 3. Analysis of variance for the listeners with hearing loss.

Main effects and interactions	*df*	*F*	*p*	η_p^2
Compression	1, 32	0.132	.719	.04
Age	1, 32	4.260	**.047**	.117
PI	1, 32	272.721	**< .001**	.895
Noise	1, 32	3.355	.076	.095
Noise × Age	1, 32	4.408	**.044**	.121
Noise × PI	1, 32	7.878	**.008**	.198
Noise × Age × PI	1, 32	0.735	.398	.022
Age × PI	1, 32	0.018	.895	.001
Compression × Noise	1, 32	0.032	.859	.001
Compression × PI	1, 32	1.121	.298	.034
Compression × Age	1, 32	0.207	.652	.006
Compression × PI × Age	1, 32	0.154	.698	.005
Compression × Noise × Age	1, 32	0.713	.405	.022
Compression × PI × Noise	1, 32	0.064	.802	.002
Compression × PI × Noise × Age	1, 32	0.191	.665	.006

Note. PI = performance-intensity point. Bold values indicate $p < .05$.

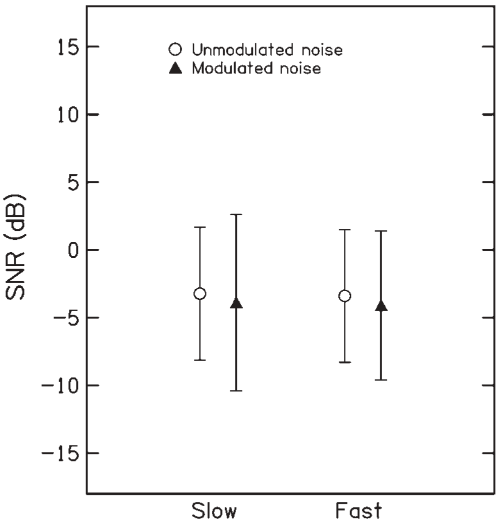
performance-intensity point. Masking release occurred with fast WDRC for the adults but not the children.

Discussion

Age and Hearing Status

In contrast to other studies (Bernstein & Grant, 2009; Hall et al., 2012; Jin & Nelson, 2010; Lorenzi et al., 2006; Peters et al., 1998; Summers & Molis, 2004), masking release did not depend on hearing status for the adults. Differences in results between this study and other studies may be attributable to differences in the audibility of the speech signal, the small amount of masking release observed in this study, and differences in the modulated maskers. Bacon et al. (1998) and Summers and Molis (2004) demonstrated that audibility contributes to masking release. The use of amplification in the present study may have resulted in improved audibility during dips in the masker level compared with, for example, the participants in Hall et al. (2012), who were not provided with amplification. Another difference was that masking release was smaller for the present study than for earlier studies. This limited the ability to detect differences across groups in the present study. The small amount of masking release may have been due to the use of a masker with less modulation depth than that in other studies (e.g., Hall et al., 2012). However, the type of masker used in this study is more similar to the type of modulated noise that people listen to in noisy environments, such as a restaurant.

Figure 7. Signal-to-noise ratio (SNR) for slow and fast wide dynamic range compression, averaged across the two performance-intensity points. Includes both children and adults with hearing loss.



The results of this study support the idea that adults with hearing loss are better able to benefit from a modulated masker compared with children with hearing loss. This pattern of results gives credence to the notion that children are less able to extract speech from noise, possibly due to limited experience listening in noise or other factors such as slower cognitive processing speed (Fry & Hale, 2000). Previous studies have shown that older adults with normal hearing exhibit poorer overall speech recognition (in unmodulated and modulated noise) and less benefit from a modulated masker than younger adults with normal hearing (Dubno, Horwitz, & Ahlstrom, 2002, 2003). However, thresholds in these previous studies were not matched between the two age groups (young adults, older adults). Füllgrabe, Moore, and Stone (2015) found that masking release was equivalent for older and younger adults when the two groups were matched for hearing thresholds, suggesting that differences in audibility, not age, may have contributed to the smaller masking release of the older age group for the studies by Dubno and colleagues. Because more children had experience with amplification than adults, it is possible that, if hearing-aid experience improves the ability to listen in the dips, hearing-aid experience interacted with age to reduce differences in masking release between the two groups.

Compression Speed

Fast WDRC did not give significantly greater masking release than slow WDRC. Thus, the findings do not lend support to the hypothesis that fast WDRC improves the ability to perceive speech in the dips by improving the audibility of the speech signal. The modulation depth of the stimuli was smaller with fast than slow compression (see Figure 2 [panel b]), suggesting that fast compression was effective at improving audibility during dips in the masker level. There are a number of possible explanations for the current findings. Participants with hearing loss may have been unable to take advantage of the improved audibility of the speech signal associated with fast WDRC due to potentially abnormal temporal resolution (Bacon & Viemeister, 1985; Florentine & Buus, 1984; Füllgrabe, Meyer, & Lorenzi, 2003), increased distortion of temporal cues caused by WDRC (Plomp, 1988), comodulation of the speech and noise caused by WDRC (Stone & Moore, 2007, 2008), decreased overall SNR due to increased (amplified) low-level masker noise when speech was not present (Alexander & Masterson, 2015; Naylor & Johannesson, 2009; Souza, Jenstad, & Boike, 2006), or variability in cognition among participants (e.g., Lunner & Sundewall-Thoren, 2007). The use of a slower compression speed, or even linear amplification, might have revealed a larger effect of compression speed. As mentioned previously, Souza et al. (2006) used the envelope of 12 talkers to modulate broadband noise and did not see a benefit from the fluctuating masker, even for participants with normal hearing. In contrast, Hall et al. (2012) used speech-shaped noise that was modulated at 10 Hz with 100% depth and found masking release of 5 dB for their adult participants with normal hearing. One possible consequence of the use of more realistic maskers in Souza et al. and in this study is that the potential benefit of fast relative to slow WDRC was reduced because of the limited temporal fluctuations.

SNR

Although masking release was closer to zero at the 70% than at the 30% point, this was true of both the normal hearing and hearing loss groups. The smaller masking release at the 70% point is consistent with previous work that demonstrated that masking release is greater when the SNR is lower (e.g., Bernstein & Grant, 2009). Keep in mind, however, that despite masking release having been measured at a lower SNR for the listeners with normal hearing than for the listeners with hearing loss, the small amount of masking release was similar for the two groups.

Conclusions

Speech recognition in noise was better for participants with normal hearing than for those with hearing loss and was higher for adults than for children, consistent with the existing literature. Adults with SNHL showed greater masking release than children with SNHL. When comparing fast WDRC for the participants with hearing loss to speech recognition for the participants with normal hearing, there was no effect of hearing loss on masking release. This finding is in contrast to previous investigations of masking release for participants with hearing loss. It is hypothesized that this difference can be attributed to the additional audibility of speech in the dips of the masker provided by the fast WDRC in this study. However, the small amount of masking release that occurred might have limited the ability to detect a difference in masking release between the groups.

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