Published in final edited form as:

Ear Hear. 2018 ; 39(5): 969–979. doi:10.1097/AUD.0000000000000558.

The influence of hearing-aid gain on gap-detection thresholds for children and adults with hearing loss

Marc A. Brennan¹, Ryan W. McCreery², Emily Buss³, and Walt Jesteadt²

¹University of Nebraska-Lincoln, Lincoln, NE 68583

²Boys Town National Research Hospital, Omaha, NE 68131

³University of North Carolina, Chapel Hill, NC 27599

Abstract

Objectives—The objective of this experiment was to examine the contributions of audibility to the ability to perceive a gap in noise for children and adults. Sensorineural hearing loss in adulthood is associated with a deficit in gap detection. It is well known that reduced audibility in adult listeners with sensorineural hearing loss contributes to this deficit; however, it is unclear the extent to which hearing-aid amplification can restore gap-detection thresholds, and the impact of childhood sensorineural hearing loss on gap-detection thresholds have not been described. For adults, it was hypothesized that restoring the dynamic range of hearing for listeners with sensorineural hearing loss would lead to approximately normal gap-detection thresholds. Children with normal hearing exhibit poorer gap-detection thresholds than adults. Due to their hearing loss, children with sensorineural hearing loss have less auditory experience than their peers with normal hearing. Yet, it is unknown the extent to which auditory experience impacts their ability to perceive gaps in noise. Even with the provision of amplification, it was hypothesized that children with sensorineural hearing loss would show a deficit in gap detection, relative to their normal-hearing peers, due to reduced auditory experience.

Design—The ability to detect a silent interval in noise was tested by adapting the stimulus level required for detection of gap durations between 3 and 20 ms for adults and children with and without sensorineural hearing loss. Stimulus-level thresholds were measured for participants with sensorineural hearing loss without amplification and with two prescriptive procedures—the adult and child versions of the Desired Sensation Level i/o program—using a hearing-aid simulator. The child version better restored the normal dynamic range than the adult version. Adults and children with normal hearing were tested without amplification.

Results—When fitted using the procedure that best restored the dynamic range, adults with sensorineural hearing loss had stimulus-level thresholds similar to those of normal-hearing adults. Compared to the children with normal hearing, the children with sensorineural hearing loss required a higher stimulus level to detect a 5-ms gap, despite having used the procedure that better

Address correspondence to Marc Brennan, University of Nebraska-Lincoln, 274 Barkley Center, Lincoln, NE 68583; fax: 402 472 7697; phone: 402 472 3079; marc.brennan@unl.edu.

Portions of this dataset were presented at the International Hearing Aid Research Conference, Lake Tahoe, Nevada, August 13, 2016.

restored the normal dynamic range of hearing. Otherwise the two groups of children had similar stimulus-level thresholds.

Conclusion—These findings suggest that apparent deficits in temporal resolution, as measured using stimulus-level thresholds for the detection of gaps, are dependent on age and audibility. These novel results indicate that childhood sensorineural hearing loss may impair temporal resolution as measured by stimulus-level thresholds for the detection of a gap in noise. This work has implications for understanding the effects of amplification on the ability to perceive temporal cues in speech.

INTRODUCTION

This study examined the ability of adults and children with sensorineural hearing loss (SNHL) and normal hearing (NH) to detect a silent interval (gap) in noise. The perception of gaps in noise is of interest because listeners with better gap-detection thresholds can have superior speech recognition compared to listeners with poorer gap-detection thresholds (e.g. Feng et al. 2009; Glasberg & Moore 1989; Helfer & Vargo 2009; but see Gordon-Salant 1993; Haubert & Pichora-Fuller 1999). As a consequence, understanding the effects of amplification on gap detection is an important step towards modifying prescriptive procedures to improve access to temporal information. The ability to detect a gap is typically measured by varying the duration of the silent interval until a certain criterion correct detection—e.g. 71%—is obtained, referred to here as gap-duration threshold. Most studies to date compared gap detection for listeners with SNHL and NH at equal sensation level (SL; Horwitz et al. 2011), sound-pressure level (SPL; Florentine & Buus 1984; Hall et al. 1998; Irwin et al. 1981), or both (Glasberg et al. 1987; Glasberg & Moore 1989). Few studies have determined the extent to which hearing-aid amplification applied to the stimulus can improve gap-detection thresholds (Glasberg & Moore, 1992; Moore et al. 2001), and studies to date have not examined the impact of childhood SNHL on the ability to perceive a gap in noise.

The present study examined changes in the ability to perceive a gap in adults with SNHL with 2 prescriptive procedures and compared these thresholds to those of listeners with NH without hearing-aid amplification. The dynamic range of hearing was greater for the participants with NH than with SNHL. For the participants with SNHL, the dynamic range of hearing was larger when aided than unaided. These variations in the audible dynamic range limited our ability to select stimulus levels that spanned the dynamic range of hearing across conditions and hearing status; our solution was to use the same fixed gap durations across conditions and groups, and adaptively vary the stimulus level (Fitzgibbons 1983). Because children with NH show poorer gap-duration thresholds than adults with NH (Buss et al. 2014; Irwin et al. 1985; Wightman et al. 1989), children were also tested to determine the influence of age and amplification on stimulus-level thresholds.

Auditory temporal resolution is a measure of the ability of a listener to perceive changes in level over time. The detection threshold for a gap in noise is one such measure of temporal resolution. Other measures of temporal resolution include threshold for detecting a sinusoidal modulator applied to a carrier signal (AM detection: Bacon & Viemeister 1985), a

target that temporally follows a masker (forward masking: Jesteadt et al. 1982), difference in signal duration (duration discrimination: Abel 1972), or a target sound in the presence maskers with coherent envelope fluctuation across frequency (e.g. comodulation masking release Hall & Grose, 1994). Spectral cues can play a role in the perception of temporal information, in that listeners may use spectral information that varies by frequency over time. Most studies of temporal resolution limit the availability of spectral information by, for example, masking the spectral information that occurs when a gap is inserted into a sinusoid or narrowband noise (e.g. Moore et al. 1992) or, as was done in the current study, using broadband noise—where presumably the spectral splatter is not detectable.

The ability to detect a gap in noise is affected by the stimulus SL, bandwidth, and center frequency. For listeners with NH, gap-duration thresholds are reduced (improved) as the stimulus SL is increased up to approximately 30 dB SL (Davis & McCroskey 1980; Florentine & Buus 1984; Horwitz et al. 2011; Plomp 1964; Zeng et al. 2005). Thresholds also improve as the bandwidth of the stimulus is increased (Eddins et al. 1992; Fitzgibbons 1983; Glasberg & Moore 1992; Hall et al. 1998), and in some cases, as the stimulus bandwidth and center frequency are increased simultaneously (Moore & Glasberg 1988; Shailer & Moore 1983). When listeners with NH and listeners with SNHL are tested at the same SPL, the reduction in audibility associated with SNHL can result in poorer gap detection (Florentine & Buus, 1984; Glasberg et al. 1987; Glasberg & Moore 1989; Grose et al. 1989; Irwin et al. 1981; Moore & Glasberg 1988). However, little difference remains when the comparison is made at an equal SL (Fitzgibbons & Wightman 1982; Glasberg et al. 1987; Glasberg & Moore 1989; Horwitz et al. 2011). Florentine & Buus (1984) showed that using masking noise spectrally shaped to simulate the hearing loss of the listeners with SNHL could mimic gap-duration thresholds in impaired ears. Together, these studies suggest that diminished audibility (i.e., reduced SL) can account for differences in gap-duration thresholds between listeners with and without SNHL.

Hearing-aid amplification can compensate for reduced audibility in listeners with SNHL by applying frequency-specific gain, which is set based on audiometric thresholds using a prescriptive procedure (e.g. Keidser et al. 2011; Moore et al. 2010; Scollie et al. 2005). As a consequence of differences in the suggested gain across prescriptive procedures, these procedures differ in the extent to which they map the normal dynamic range of hearing to the smaller dynamic range of listeners with hearing loss—especially for low-level inputs, as described below. Figure 1 shows the output for the same broadband noise (100 – 8000 Hz) used in this study with the adult and child versions of the Desired Sensation Level i/o program (Scollie et al. 2005); targets were based on the hearing loss of an adult who participated in this study. The adult version of the Desired Sensation Level i/o program (DSL-A) prescribes less gain than the child version (DSL-C) because many adults do not tolerate the higher output of DSL-C (Scollie et al. 2005); consequently, audibility is greater with DSL-C than DSL-A. Specifically, for an equivalent noise level, the sensation level is higher and more bandwidth is audible for the listener, particularly at low input levels. Put differently, more of the normal dynamic range of hearing is mapped to that of the impaired listeners with DSL-C than DSL-A. The extent to which loss of audibility is compensated for will also depend upon how quickly the hearing aid adjusts its gain to changes in the input level—i.e. the compression speed. For lower stimulus levels, a faster compression speed will

more effectively increase the level of the stimulus, especially for shorter gap durations, which should support better gap-detection thresholds. A faster compression speed will also more effectively reduce inherent fluctuations in the stimulus, which has been shown to improve gap-duration thresholds for noise bandwidths of 100 Hz or less (Glasberg & Moore 1992; Moore et al. 2001).

It is not clear the extent to which different prescriptive procedures or compression speeds result in performance for listeners with SNHL that approximate that of listeners with NH. Because gap-duration thresholds improve with increased SL and bandwidth, we expect the DSL-C procedure, which maps a larger portion of the normal dynamic range to that of the impaired dynamic range than DSL-A, to result in thresholds that most effectively approximate those of the listeners with NH. An alternative outcome is that DSL-A sufficiently restores audibility to approximate the thresholds of the listeners with NH. Three studies have tested the effects of audibility on temporal resolution by measuring gap-duration thresholds using amplification (Brennan et al. 2013; Glasberg & Moore 1992; Moore et al. 2001). All 3 studies examined the effect of compression amplification on gap detection; none investigated the influence of the prescriptive procedure on gap-detection thresholds. The studies by Moore and colleagues set amplification either to obtain an equal SL for an equivalent input level between the impaired and normal ears (Glasberg & Moore 1992) or using the default manufacturer prescriptive procedure (Moore et al. 2001). In both studies, the hearing-impaired listeners exhibited poorer gap-duration thresholds than the listeners with NH, even with the provision of amplification. Brennan et al. (2013) used amplification set to DSL-C in their listeners with SNHL and found that the mean gap-duration threshold for 60 dB SPL broadband noise was approximately 3 ms, similar to gap-duration thresholds previously reported for listeners with NH in broadband noise at that level (Irwin et al. 1981).

The influence of the compression speed on the detection of gaps is uncertain. Glasberg and Moore (1992), using instant compression, found improved detection of gaps compared to linear amplification—when the bands of noise were 100 Hz or less. A follow-up study found that the use of fast-acting compression (15-ms attack time, 30-ms release time), relative to slow compression (300-ms attack time, 3-second release time), improved the detection of gaps in narrow bands of noise (Moore et al. 2001). In contrast, Brennan et al. (2013) found that gap-duration thresholds did not vary between a condition with fast compression (1-ms attack time, 10-ms release time) and one with linear amplification for a narrowband noise carrier (10 Hz wide) or a wideband noise carrier. Only a single stimulus level was presented in the above studies. What is missing is detailed knowledge about the relationship between gap-detection thresholds, stimulus level, the prescriptive fitting procedure, and compression speed for participants with SNHL; and also the extent to which prescriptive procedures result in thresholds that approximate those of the listeners with NH.

Information on the effect of the prescriptive fitting procedure and compression speed on the detection of gaps in noise could be useful for our pediatric patients with SNHL. Compared to adults, children rely more on the acoustic than linguistic information in speech (e.g. Craig et al. 1993). With the exception of one study (Chermak & Lee 2005), most studies have found poorer gap-duration thresholds in children than in adults with NH (Buss et al. 2014;

Davis & McCroskey 1980; Irwin et al. 1985; Trehub et al. 1995; Werner et al. 1992; Wightman et al. 1989). Adult-like resolution varies with the procedures and stimuli used, but appears to occur by approximately 10 years of age (Buss et al. 2014; Irwin et al. 1985; Wightman et al. 1989; Buss et al. 2017). We know of no studies that examined gap-detection thresholds in children with SNHL. Balen et al. (2009) found poorer gap-detection thresholds in children with presumed conductive hearing loss relative to children with NH. Hall and Grose (1994) showed that co-modulation masking release, another measure of temporal resolution, was poorer for children with temporary hearing loss secondary to otitis media compared to a control group without such history. However, Rance et al. (2004) observed that children with and without SNHL had similar thresholds for the detection of amplitude modulations. These results suggest that hearing loss in childhood may degrade temporal resolution, although it is not clear that the effects observed for the children with conductive hearing loss would apply to children with SNHL.

The mechanisms that contribute to development of gap perception in children are unclear but may be related to maturation of the nervous system, including the development of attention, motivation, and/or cognition (Buss et al. 2014; Davis & McCroskey 1980; Trehub et al. 1995). Development of intensity discrimination could also play a role in gap detection, in that children are less sensitive to dynamic changes in stimulus level than adults (Buss et al. 2017). Higher internal noise in children may also cause poorer gap-detection thresholds in children (Buss et al. 2014). We predict that limited auditory experience in children with NH could explain their poorer performance relative to adults with NH. Because SNHL in children results in less auditory experience relative to children with NH, we hypothesize that children with SNHL could show poorer gap-detection thresholds relative to their peers with NH.

The purpose of experiment I was to determine the effect of the prescriptive procedure, age (child, adult) and hearing status on the ability to detect a gap in noise. The effect of the prescriptive procedure was assessed by testing adults with SNHL with both DSL-A and DSL-C. The effect of age and hearing status was tested by comparing stimulus-level thresholds obtained with DSL-C in adults and children with SNHL to unaided thresholds obtained in adults and children with NH. The purpose of experiment II was to determine the extent to which varying the compression speed influences gap-duration thresholds. Experiment III examined the validity of obtaining stimulus-level thresholds as a measure temporal resolution by examining the relationship between stimulus-level thresholds and gap-duration thresholds. The hypotheses were:

- The child participants, especially the children with SNHL, would show poorer stimulus-level thresholds than the adults.
- Because DSL-C better maps the impaired dynamic range to that of the normal dynamic range, stimulus-level thresholds would be best with DSL-C and would most closely mimic results obtained with the listeners with NH.
- Because fast compression better restores the dynamic range of hearing, thresholds were expected to improve with a faster compression speed relative to a slower compression speed.

- Equivalent thresholds would be obtained whether adapting on the stimulus level or the gap duration.

MATERIALS AND METHODS

Participants

Experiment I included 15 adults with NH (age in years: Median = 59, Mean = 54, SD = 14), 15 adults with SNHL (age in years: Median = 57, Mean = 53, SD = 14), 14 children with NH (age in years: Median = 11, Mean = 11, SD = 3) and 14 children with SNHL (age in years: Median = 11, Mean = 11, SD = 3). The older children with NH had higher pure-tone averages (PTA: 2, 4 and 6 kHz) than the younger children with NH ($r = .59$, $p = .025$), but there was no association between age and PTA for the children with SNHL ($r = -.18$, $p = .534$). The age range for children was selected to span a range known to show improvements in gap-duration thresholds with increased age (Buss et al. 2014; Irwin et al. 1985; Wightman et al. 1989). Each adult with NH was age matched to within 5 years of an adult with SNHL. Ten of the normal-hearing children in Experiment I were age matched to within 6 months of a child with SNHL, and the remaining four were matched to within 1 year. An audiologist measured hearing thresholds (re: ANSI 2004) for all participants using pure-tone audiometry (ASHA 2005) at octave frequencies from 250 to 8000 Hz using Telephonics TDH-50P headphones (Farmingdale, NY) or Etymotic Research 3A (Elk Grove Village, IL) insert earphones. The pure-tone thresholds for each participant group are depicted in Figure 2. Pure-tone thresholds were not obtained in 4 children with NH. Instead, hearing was tested in these children by obtaining responses at 15 dB HL. Their results are not plotted in Figure 2.

Experiment II included 8 adults with SNHL (age in years: Median = 48, Mean = 50, SD = 13), and experiment III included 7 adults with NH (age in years: Median = 35, Mean = 34, SD = 9). All participants were native English speakers. Data were collected at Boys Town National Research Hospital, and approval for this study was obtained from the Institutional Review Board. Participants consented to join the study and were reimbursed monetarily (\$15 per hour) for their time.

Apparatus

Digital stimuli (22.05 kHz sampling rate) were converted to analog (RME Babyface sound card, Haimhausen, Germany), routed via a MiniMon Mon800 monitor matrix mixer (Behringer, Kirchardt, Germany), amplified with a PreSonus HP4 headphone distribution amplifier (Baton Rouge, Louisiana), and presented to one ear using Sennheiser HD-25 headphones (Wedemark, Germany). All testing took place in a double-walled sound attenuated room.

Stimuli

Stimuli were generated using a PC and custom MATLAB (2009b) scripts. The stimulus was white noise from 100 to 8000 Hz, 400 ms in duration with 5-ms cosine-squared onset and offset ramps. Prior to each trial, two noise stimuli, equated in level, were generated in the frequency domain using sine waves spaced at 1-Hz intervals—each with a random start phase. A gap was created by removing a portion of the stimulus, centered on the temporal

midpoint and shaped with 2-ms cosine-squared ramps. The gap durations, defined from the 6-dB-down points (i.e. 0-voltage intervals plus 2 ms), were 3, 5, 10, 15, 20, and 25 ms. Stimuli were calibrated by calculating the root-mean-square average for the standard (no gap) stimuli in a 6-cc flat plate coupler (AEC101, Larson Davis, Provo, Utah) using a Larson Davis System 824 sound level meter (Provo, Utah).

Amplification

Stimuli were amplified for the adults and children with SNHL using a hearing-aid simulator implemented in MATLAB (2009b). Only a short overview of the processing is presented, as this simulator has already been described (e.g. Brennan et al. 2015). The hearing-aid simulator consisted of a filterbank (see Table 1), wide-dynamic-range compression (WDRC; 5-ms attack time, 10-ms release time) and output compression (1-ms attack time, 50-ms release time). Although faster than the WDRC time constants used in commercially available hearing aids, these fast attack and release times were used because they were previously found to support better forward-masked tone detection in adults with SNHL than slower attack and release times (Brennan et al. 2015). Experiment II examined the influence of the compression speed on stimulus-level thresholds by measuring thresholds using fast WDRC (5-ms attack time, 10-ms release time) and slow WDRC (50-ms attack time, 150-ms release time) with the DSL-C prescriptive procedure.

Thresholds in dB SPLⁱ were entered into the DSL program, which generated the WDRC and output compression kneepoints, the target-output levels for conversational speech, and maximum output. To test the influence of the dynamic range on stimulus-level thresholds, targets were generated for both DSL-A and DSL-C for the adults. To reduce test time, only DSL-C targets were generated for the children. The WDRC and output compression kneepoints were set to the DSL prescribed levels. However, the maximum output compression kneepoint allowed was 105 dB SPL. Output levels for the long-term average speech spectrum (overall level of 60 dB SPL; Byrne et al. 1994) were set to within 5 dB of DSL targets.

For experiment I—across participants and hearing-aid channels—the kneepoint varied from 18 to 58 dB SPL. The kneepoint for each hearing-aid channel, averaged across participants, varied from 32 to 37 dB SPL. The range and average kneepoints were similar for the adults and children with SNHL. The compression ratios for the noise stimuli without a gap (i.e., the standard stimuli) were measured. This was done by computing the SPL after amplification for one-third octave filters centered at 1, 2, and 4 kHz for noise input levels of 30 and 50 dB SPL (spanning most of the range of stimulus-level thresholds observed in this study), for each subject. The mean compression ratios (SD in parenthesis) for each frequency, respectively, were 1.0 (.10), 1.1 (.10), and 1.2 (.16) for DSL-A and 1.2 (.16), 1.2 (.17), and 1.5 (.24) for DSL-C. The spectra of example stimuli are shown in Figure 3, left column. Due

ⁱTransfer functions from dB HL to SPL were derived for both the TDH headphones and 3A insert earphones attached to a Knowles Electronic Manikin for Acoustic Research (KEMAR) with an IEC 711 coupler (G.R.A.S. Sound & Vibrations, Holte, Denmark) and the Larson Davis System 824 sound level meter. Using the appropriate transfer function, hearing thresholds in dB HL from the audiometric testing were converted to dB SPL. Output levels with the hearing-aid simulator were estimated using a transfer function derived from the Sennheiser HD-25-1 headphones—used for stimuli presentation—attached to KEMAR and the Larson Davis System 824 sound level meter.

to the provision of amplification, output is greater for the higher than lower frequencies. The spectrum did not differ between the standard and target stimuli (top and bottom rows, respectively). The waveforms for a standard stimulus with DSL-C are shown in Figure 3, right column. Due to the 3-dB greater output with fast than slow WDRC, the amplitudes were greater with fast WDRC (top and bottom rows, respectively). As expected, the use of broadband noise resulted in a similar envelope with the two compression speeds.

Procedure

For experiments I and II, the adults and children sat in front of a touch-screen monitor. For each of the five fixed gap durations, the SPL of the stimuli—prior to amplification for those conditions—was adapted using a 3-interval forced-choice task with a 2-down 1-up rule (Levitt, 1971) to determine the level of the noise required for detection of the gap, referred to here as the stimulus-level threshold. The starting level was 60 dB SPL. Level adjustments were made in steps of 18 dB prior to the first reversal, 9 dB between the first and second reversal, 6 dB between the second and third reversal, and 3 dB for the remaining four reversals. The average of these four reversals was taken as threshold. The minimum level was 0 dB SPL, and the maximum level was 85 dB SPL. Threshold was recorded as 88 dB SPL if a listener's track stayed at the maximum level for more than 2 trials in a row. No track stayed at the minimum level. A trial consisted of 3 observation intervals separated by 300 ms. Each observation interval was 1200 ms in duration and was marked by a separate button that lit up on the touch-screen monitor. The 400-ms stimuli were temporally centered in each observation interval. Participants indicated the interval that they thought contained the target by pressing the associated button. Feedback was provided.

Adults were tested with 2 prescriptive procedures (DSL-A, DSL-C) and unaided. Children were tested with DSL-C and unaided. Participants practiced by obtaining 2 stimulus-level threshold estimates with a 25-ms gap duration. The prescriptive procedure used for practice was randomly selected for each adult with SNHL. Children with SNHL practiced with DSL-C. For the experimental task, thresholds were estimated twice for each condition. For the adults, if the 2 threshold estimates differed by more than 6 dB, threshold was estimated a third time. Due to the limited attention span of the younger children, we only collected data for 2 blocks for the child participantsⁱⁱ. Thresholds for each condition were averaged across the 2 or 3 blocks obtained. One subject had thresholds at ceiling for 2 of the 3 blocks for the 15 ms stimulus-level condition. For this subject and condition, threshold was taken as the estimated threshold for the single block that was not at ceiling. For the participants with SNHL, the unaided thresholds were collected after the aided thresholds. Unaided thresholds were obtained on all of the children with SNHL and on 6 of the 15 adults with SNHL. Unaided stimulus-level thresholds were only measured on some adults because we added this additional paradigm to the experiment following initial data collection. Otherwise, the order of conditions was randomized.

For experiment III, which examined whether stimulus-level and gap-duration thresholds provide a similar estimate of temporal resolution, stimulus-level thresholds were obtained

ⁱⁱThe first two blocks differed by more than 6 dB 23 and 25 times for the adults and children with SNHL, respectively. Using the third block to estimate threshold for the adults with SNHL changed the mean threshold by an average of .1 dB.

using the same procedure described previously. The stimulus-level thresholds were then used to set the stimulus levels for the gap-duration thresholds. Specifically, the stimulus levels for the gap-duration thresholds were set individually for each participant and were the same as the stimulus-level thresholds for the 5-, 10-, 15-, and 20-ms gap durations. For each of the 4 stimulus levels tested for an individual, it was expected that the gap-duration threshold would be similar to the corresponding gap duration (e.g., 5 ms for the stimulus-level that corresponded to the stimulus-level threshold for a 5-ms gap duration). The gap duration started at 10 ms above the expected gap threshold (e.g., 25 ms for the stimulus level corresponding to the 15-ms gap duration). The gap duration was varied by a factor of 2.8 prior to the first reversal, by a factor of 1.4 prior to the second reversal, and by a factor of 1.2 for the remaining 4 reversals. The geometric mean of the last 4 reversals was taken as threshold. Thresholds were estimated twice for each stimulus level. If the 2 threshold estimates differed by more than 5 ms, threshold was estimated a third time. Thresholds for each condition were averaged, using the geometric mean, across the 2 or 3 blocks obtained. Data collection for each experiment took 1–2 sessions that lasted up to 3 hours each.

Analysis

The different participant groups and conditions for each experiment are shown in Table 2. The majority of participants did not obtain a valid threshold for the 3-ms gap duration; these participants were at ceiling. For that reason, we excluded the 3-ms gap duration data from the following statistical analyses. Due to the small number of adults with SNHL tested in the unaided condition, the unaided data for the participants with SNHL were not analyzed. Three ANOVAs were completed. The first ANOVA was completed on the stimulus-level thresholds for the adults with SNHL to determine the effect of the prescriptive procedure (DSL-A, DSL-C) on thresholds for each gap duration (5, 10, 15, 20 ms). The second ANOVA determined the effect of hearing status and age group on stimulus-level thresholds with factors gap duration (5, 10, 15, 20 ms), age group (children, adults), and hearing status (NH, SNHL). Unaided stimulus-level thresholds for the adults and children with NH were compared to stimulus-level thresholds with DSL-C for the adults and children with SNHL. The last ANOVA determined the effect of compression speed (fast, slow) on thresholds for each gap duration (5, 10, 15, 20 ms) when using the DSL-C prescriptive procedure. For all ANOVAs, Mauchly's Test of Sphericity was used. In cases where the assumption of sphericity was violated, the degrees of freedom were adjusted for using the Greenhouse-Geisser correction. Post-hoc analyses consisted of Tukey's test for Honestly Significant Differences (HSD).

For the children, bivariate correlations and a linear mixed model, using the lme4 package for R (Bates et al. 2014), were completed to evaluate the contribution of age and degree of hearing loss to thresholds. Due to hearing thresholds not being measured, the 4 children with NH who were screened at 15 dB HL were not included in this analysis. Corrections for multiple comparisons were not applied to the bivariate correlations. However, the linear mixed model allowed for the examination of correlated random effects within participants due to repeated measures. Lastly, to determine if stimulus-level and gap-duration thresholds provide a similar estimate of temporal resolution, a priori t-tests were completed on the gap-

duration thresholds for the adults with NH in experiment III to determine if the gap-duration thresholds differed significantly from each gap duration (5, 10, 15, 20 ms).

RESULTS

Effect of the Prescriptive Procedure on Stimulus-Level Thresholds (Experiment I)

The left plot of Figure 4 depicts the stimulus-level thresholds for the adults with SNHL as filled symbols. Thresholds for the children with SNHL are shown in the right plot of Figure 4 as filled symbols. Again, the children with SNHL were only tested unaided and with DSL-C. The participants with NH are shown as unfilled circles (adults) and unfilled squares (children). An ANOVA was completed to determine the effect of the gap duration and prescriptive procedure on the stimulus-level thresholds for the adults with SNHL and is shown in Table 3 under the model prescriptive procedure. As expected, the stimulus level required to detect the gap decreased significantly as the gap duration increased. Using Tukey's test for HSD, differences of 10.7 dB between different gap durations were considered statistically significant. Thresholds were significantly lower with 10, 15, and 20 ms compared to 5 ms. Differences in threshold between 10, 15, and 20 ms were not statistically significant. Threshold was significantly lower with DSL-C than DSL-A. There was not a significant interaction of the gap duration with the prescriptive procedure. These findings demonstrated that thresholds for the adults with SNHL were significantly lower with DSL-C than DSL-A for all gap durations.

Effect of Hearing Status and Age on Stimulus-Level Thresholds (Experiment I)

An ANOVA to determine the effect of gap duration, age and hearing status on stimulus-level thresholds was completed and is shown in Table 3 under the model hearing status and age. For the participants with SNHL, the DSL-C stimulus-level thresholds were included in the model, and for the participants with NH, the unaided stimulus-level thresholds were included in the model. There was a significant interaction of gap duration, hearing status, and age group (Tukey's HSD = 12.4 dB). This three-way interaction reflects three data patterns. First, thresholds improved from the 5- to 10-ms gap duration for all groups except the children with NH. For this group, thresholds were not statistically different between 5 and 10 ms. For all groups, thresholds were significantly better at 15 and 20 ms than at 5 ms. Second, the adults with NH (unaided) and SNHL (DSL-C) had thresholds that were statistically indistinguishable for all gap durations. In contrast, the children with SNHL, when aided with DSL-C, had a significantly poorer threshold at 5 ms than the unaided children with NH. Thresholds were not statistically different between the children with and without SNHL at all other gap durations. Third, while the children and adults with NH had thresholds that were statistically indistinguishable for all gap durations, the children with SNHL had thresholds that were significantly poorer than the adults with SNHL for gap durations of 5 and 10 ms. The main effects of age and gap duration and the two-way interactions between hearing status and gap duration were significant. There was not a significant interaction of age group with hearing status. These main effects and interactions should be interpreted in the context of the significant three-way interaction.

To examine the effect of development and hearing loss on the ability to perceive a gap in noise, the stimulus-level thresholds within the child dataset (NH: unaided, SNHL: DSL-C) were plotted against age in Figure 5 and PTA threshold in Figure 6. Above each plot, the bivariate correlations of age and PTA with stimulus-level threshold are provided. The two groups (NH, SNHL) were collapsed together for the bivariate correlations. Age did not correlate significantly with stimulus level thresholds for any of the gap durations. Stimulus-level thresholds were positively correlated with PTA for the 5-ms gap duration, but not for any of the other gap durations. These effects of age and hearing loss on temporal resolution, for the children, were further examined using a mixed linear model—shown in Table 4. The random intercept variances were 39 dB (sd=5.07) and 143 dB (sd=22.8) for the random effects of participant and gap duration, respectively. Age significantly predicted stimulus-level thresholds, but PTA did not. The model estimated a 2.2-dB-SPL improvement in stimulus-level threshold for each one-year increase in age.

Effect of Compression Speed on Stimulus-Level Thresholds (Experiment II)

Figure 7 shows the stimulus-level thresholds with slow and fast WDRC for eight adults with SNHL using the DSL-C prescriptive procedure. An ANOVA to determine the effect of the gap duration and compression speed on stimulus-level thresholds was completed and is shown in Table 3. Stimulus-level thresholds decreased significantly as the gap duration increased. Thresholds were not significantly different for the two compression speeds, and the compression speed did not interact significantly with gap duration.

Gap-Duration Thresholds Compared to Stimulus-Level Thresholds (Experiment III)

In this experiment, stimulus-level thresholds were initially obtained and are shown in Table 5, second column. Following the collection of the stimulus-level thresholds, gap-duration thresholds were measured and are shown in the third column. As expected, the stimulus-level thresholds decreased as the gap duration increased. For each stimulus level, the obtained gap-duration thresholds were 1–4 ms greater than the expected threshold. One-sample t-tests, to determine whether the gap-duration thresholds were statistically different from the gap durations associated with each stimulus level, are also shown. However, none of the obtained gap-duration thresholds were significantly different than expected. These results suggest that thresholds obtained by varying the stimulus level or by varying the gap duration provide similar information about temporal resolution.

DISCUSSION

Stimulus-level thresholds were assessed in adults with SNHL using two prescriptive procedures (DSL-A, DSL-C) and two compression speeds (fast: 5-ms attack time, 10-ms release time; slow: 50-ms attack time, 150-ms release time). The prescriptive procedure that more closely restored the normal dynamic range of hearing (DSL-C) improved adults' stimulus-level thresholds when compared to a procedure that did not (DSL-A), supporting our hypothesis that the prescriptive procedure affects the ability to detect a silent interval in noise. Thresholds obtained using both procedures were better than unaided thresholds. Stimulus-level thresholds with DSL-C well approximated the performance of the listeners with NH. Compression speed did not affect stimulus-level thresholds.

Figure 8 compares our data on adults with NH from experiment I to previously obtained data. Data are reported for studies that used broadband noise presented at several levels (Fitzgibbons 1983; Florentine & Buus 1984; Irwin et al. 1981; Penner 1977; Plomp 1964). Despite the different methods used, all data show that an increase in the stimulus level is required to detect a shorter gap duration. There is overlap in the mean thresholds obtained across studies; however, note that there was a 30-dB spread in thresholds. Our data line up with those of Florentine & Buus (1984) and with the mean of the other studies. Reasons for the differences between results could include differences in stimuli parameter adjusted for threshold estimation (most adapting on the gap duration), criterion for correct detection (varied from 71–75% or subjective), the small number of subjects in each study (2–6), and differences in age of the listeners with NH. The third experiment suggests that differences in threshold estimation procedures were not a factor. While difference in age might have contributed, of those studies that reported the age of their listeners (Irwin: mean 38 years; Florentine: 20–50 years), our listeners were older on average (mean 57 years). Therefore, thresholds should have been poorer in our study—instead we observed similar or better thresholds. The range of thresholds in our study was 30–88 dB SPL at 5 ms and 14–28 dB SPL at 20 ms, which was within the range reported in other studies.

The finding that the prescriptive procedure affects the ability to perceive a gap in noise is consistent with previous research on gap detection. Minimizing differences in audibility between listeners with and without SNHL reduces discrepancies in gap-detection thresholds (Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Glasberg et al. 1987; Glasberg & Moore 1989; Horwitz et al. 2011). By providing gain that varies by frequency, prescriptive procedures differ from the traditional testing paradigm of increasing the overall noise level to equate SL between listeners with and without SNHL. Prior to this study, the extent to which hearing-aid amplification minimized differences in performance between listeners with and without SNHL was unclear. The provision of amplification using DSL-C to adults with SNHL in Brennan et al. (2013) resulted in a mean 3-ms gap-duration threshold for 60 dB SPL broadband noise, which was similar to gap-duration thresholds previously reported for listeners with NH in broadband noise at that level (Irwin et al. 1981). Brennan et al. did not test listeners with NH or obtain data at different presentation levels, however. Moore et al. (2001) found that their listeners with SNHL better detected gaps in narrowband noise (< 500 Hz) when they were provided amplification compared to unaided, although differences still remained between the listeners with and without SNHL. The present study documented the extent to which two different prescriptive procedures normalize the ability to perceive a silent interval and found that thresholds were most similar to listeners with NH when using DSL-C.

Thresholds that would be obtained for other prescriptive procedures are unclear, due in part to the fact that the prescribed output levels vary with degree of hearing loss, slope of hearing loss, and other factors (Johnson & Dillon 2011). To estimate the effect of another prescriptive procedure on thresholds, recommended target levels (for input levels of 50, 60, 70 and 80 dB SPL) were obtained using the average hearing thresholds for the adults with SNHL for DSL-C, DSL-A, and NAL-NL2 using the Verifit2 (Audioscan, Dorchester, Ontario, Canada). The following trends were observed. First, DSL-C prescribed higher output levels for all input levels than both NAL-NL2 and DSL-A; consequently, gap

detection thresholds would most likely be best with DSL-C. Second, relative to DSL-A, NAL-NL2 prescribed higher-output levels for low-level inputs but less for higher-input levels. Lastly, for all input levels, NAL-NL2 prescribed lower output-levels for frequencies above 4 kHz than DSL-A. Consequently, the relationship of thresholds obtain with NAL-NL2 to DSL-A would likely depend on whether increased audibility of low-level inputs or of high-frequency inputs contribute more to the detection of gaps in noise.

Three possible mechanisms could be responsible for the better performance with improved audibility. At higher stimulus levels, a larger dynamic range is available to represent the dip in level caused by the gap. Consequently, one idea is that higher output levels with amplification lead to improvements in the internal representation of the stimulus envelope. Another idea is that amplification improves the audible bandwidth. Both increased presentation levels and bandwidth are known to improve gap-duration thresholds (Davis & McCroskey 1980; Eddins et al. 1992; Fitzgibbons 1983; Florentine & Buus 1984; Glasberg & Moore 1992; Hall et al. 1998; Horwitz et al. 2011; Plomp 1964; Zeng et al. 2005), and each likely contributed to the improved thresholds observed with amplification in this data set. In addition to improving audibility, fast compression is known to reduce inherent envelope fluctuations in noise (e.g. Glasberg & Moore 1992). However, we do not believe that reductions in inherent envelop fluctuations influenced our findings—thresholds did not differ between the fast and slow amplification conditions. Instead, we think thresholds improved in this study due to higher output levels and/or greater audible bandwidth of the stimulus.

Prior to the current study, the impact of childhood SNHL on gap-detection thresholds was unknown. The children with SNHL—with amplification—showed poorer stimulus-level thresholds than the adults with and without SNHL and, for a 5-ms gap duration, poorer thresholds than the children with NH. In contrast, stimulus-level thresholds with DSL-C for the adults with SNHL were similar to thresholds for the adults with NH for all gap durations. Our findings are consistent with those of Hall and Grose (1994) and of Balen et al. (2009), who found that childhood conductive hearing loss impaired co-modulation masking release and gap-duration thresholds, respectively. Together these studies support the notion that childhood hearing loss, in certain stimulus conditions (e.g., with a short gap duration), may have central effects on temporal resolution—leading to a delay in the development of temporal resolution.

The mechanisms that contributed to poorer performance at only 5 ms in the present dataset are unclear; however, we hypothesize that they are related to relative changes in the excitation pattern. Due to temporal integration, which results in smearing between the masker and the silent interval, a short interval results in a smaller change in excitation level than a long silent interval. Consequently, the children with SNHL, due to reduced auditory experience, required a better representation of the stimulus envelope than adults with NH. We might have expected children to have also performed more poorly than adults for a 3-ms gap duration; however, recall that most of the adults and children could not perceive the 3-ms gap duration (i.e. thresholds were at ceiling).

Limitations of the present study include the fact that we used a hearing-aid simulator and limited the maximum presentation level to 85 dB SPL prior to amplification; both of these factors complicate interpretation of the present results with respect to performance using a commercially available hearing aid. Because the simulator does not produce acoustic feedback and has higher maximum gain than wearable devices, the hearing-aid simulator likely provided more gain than is possible with hearing aids. The ability to perceive a gap could be impeded by circuit noise in an actual hearing aid. Therefore, the potential to restore the perception of a gap might be more limited with real hearing aids. Restricting the maximum presentation level to 85 dB SPL may have restricted our ability to measure a threshold at 3 ms for some of our participants. Another limitation of the present paradigm is that restoration of audibility and/or temporal cues does not necessarily result in better speech intelligibility (e.g. Ching et al. 1998). Adjusting hearing aid parameters to maximize gap detection performance could result in a decreased signal to noise ratio (e.g. Souza et al. 2006).

Conclusion

This study determined that restoring the dynamic range of hearing in listeners with SNHL improves their ability to detect a gap in noise. We have now documented the effects of the prescriptive procedure and compression speed on stimulus-level thresholds. Except for the 5-ms gap duration threshold in children, restoring the dynamic range of hearing resulted in equivalent stimulus-level thresholds between listeners with and without SNHL. Previous work did not document the effect of childhood SNHL on gap-detection thresholds. Here we demonstrated that SNHL in children, apart from effects related to audibility, can adversely affect their ability to perceive a gap when compared to the children with NH.

Acknowledgments

We thank Alex Baker, Brianna Byllesby, Evan Cordrey, and Clairissa Mollak for help in data collection and analysis. Funding was received by grants from the NIH: R01 DC013591 (to R.M.), F32 DC12709 (to M.B.), P20 GM109023 (to M.B. & W.J.), and P30 DC4662 (to Michael Gorga). M.B. designed and performed experiments, analyzed data, and wrote the paper. All authors discussed analysis and implications, and commented on the manuscript at all stages.

References

- Abel S. Discrimination of temporal gaps. *J Acoust Soc Am*. 1972; 52:519–524.
- ANSI. Specification for Audiometers. American National Standards Institute; New York, NY: 2004. ANSI S3.6-2004.
- ASHA. Guidelines for manual pure-tone threshold audiometry. American Speech-Language-Hearing Association; Rockville, MD: 2005.
- Balen SA, Bretzke L, Mottecy CM, et al. Temporal resolution in children: comparing normal hearing, conductive hearing loss and auditory processing disorder. *Braz J Otorhinolaryngol*. 2009; 75:123–129. [PubMed: 19488572]
- Bates D, Maechler M, Bolker B, et al. lme4: Linear mixed-effects models using Eigen and S4. R package version. 2014; 1(7)
- Bacon S, Viemeister N. Temporal modulation transfer functions in normal-hearing and hearing-impaired listeners. *Audiol*. 1985; 24:117–134.
- Brennan M, Gallun FJ, Stecker GC, et al. Temporal resolution with a prescriptive fitting formula. *Am J Audiol*. 2013; 22:216–225. [PubMed: 23824436]

- Brennan MA, McCreery RW, Jesteadt W. The influence of hearing-aid compression on forward-masked thresholds for adults with hearing loss. *J Acoust Soc Am*. 2015; 138:2589–2597. [PubMed: 26520341]
- Byrne D, Dillon H, Tran K, et al. An international comparison of long-term average speech spectra. *J Acoust Soc Am*. 1994; 96:2108–2120.
- Buss E, Hall JW III, Porter H, et al. Gap detection in school-age children and adults: Effects of inherent envelope modulation and the availability of cues across frequency. *J Speech Lang Hear Res*. 2014; 57:1098–1107. [PubMed: 24686553]
- Buss E, Porter HL, Hall JW III, et al. Gap detection in school-age children and adults: Center frequency and ramp duration. *J Speech Lang Hear Res*. 2017; 60:172–181. [PubMed: 28056469]
- Chermak GD, Lee J. Comparison of children's performance on four tests of temporal resolution. *J Am Acad Audiol*. 2005; 16:554–563. [PubMed: 16295242]
- Ching TYC, Dillon H, Byrne D. Speech recognition of hearing-impaired listeners: Predictions from audibility and the limited role of high-frequency amplification. *J Acoust Soc Am*. 1998; 103:1128–1140. [PubMed: 9479766]
- Cornelisse L, Seewald R, Jamieson D. The input/output formula: A theoretical approach to the fitting of personal amplification devices. *J Acoust Soc Am*. 1995; 97:1854–1864. [PubMed: 7699167]
- Craig CH, Kim BW, Rhyner PMP, et al. Effects of word predictability, child development, and aging on time-gated speech recognition performance. *J Speech Lang Hear Res*. 1993; 36:832–841.
- Davis SM, McCroskey RL. Auditory fusion in children. *Child Dev*. 1980; 51:75–80. [PubMed: 7363751]
- Eddins DA, Hall JW III, Grose JH. The detection of temporal gaps as a function of frequency region and absolute noise bandwidth. *J Acoust Soc Am*. 1992; 91:1069–1077. [PubMed: 1556308]
- Feng Y, Yin S, Kieft M, Wang J. Temporal resolution in regions of normal hearing and speech perception in noise for adults with sloping high-frequency hearing loss. *Ear Hear*. 2010; 31:115–125. [PubMed: 19816181]
- Fitzgibbons P. Temporal gap detection in noise as a function of frequency, bandwidth, and level. *J Acoust Soc Am*. 1983; 74:67–72. [PubMed: 6886200]
- Fitzgibbons P, Wightman F. Gap detection in normal and hearing-impaired listeners. *J Acoust Soc Am*. 1982; 72:761–765. [PubMed: 7130534]
- Florentine M, Buus S. Temporal gap detection in sensorineural and simulated hearing impairments. *J Speech Lang Hear Res*. 1984; 27:449–455.
- Glasberg BR, Moore BCJ. Psychoacoustic abilities of subjects with unilateral and bilateral cochlear impairments and their relationship to the ability to understand speech. *Scand Audiol*. 1989; S32:1–25.
- Glasberg B, Moore BCJ. Effects of envelope fluctuations on gap detection. *Hear Res*. 1992; 64:81–92. [PubMed: 1490904]
- Glasberg B, Moore BCJ, Bacon S. Gap detection and masking in hearing-impaired and normal-hearing subjects. *J Acoust Soc Am*. 1987; 81:1546–1556. [PubMed: 3584692]
- Gordon-Salant S, Fitzgibbons P. Temporal factors and speech recognition performance in young and elderly listeners. *J Speech Hear Res*. 1993; 36:1276–1285. [PubMed: 8114494]
- Grose J, Eddins D, Hall J. Gap detection as a function of stimulus bandwidth with fixed high-frequency cutoff in normal-hearing and hearing-impaired listeners. *J Acoust Soc Am*. 1989; 86:1747–1755. [PubMed: 2808923]
- Hall JW III, Grose JH. Effect of otitis media with effusion on comodulation masking release in children. *J Speech Lang Hear Res*. 1994; 37:1441–1449.
- Hall JW III, Grose J, Buss E, et al. Temporal analysis and stimulus fluctuation in listeners with normal and impaired hearing. *J Speech Lang Hear Res*. 1998; 41:340–354. [PubMed: 9570587]
- Haubert N, Pichora-Fuller M. The perception of spoken language by elderly listeners: Contribution of auditory temporal process. *Can Acoust*. 1999; 27:96–97.
- Helfer KS, Vargo M. Speech recognition and temporal processing in middle-aged women. *J Am Acad Audiol*. 2009; 20:264–271. [PubMed: 19927698]

- Horwitz AR, Ahlstrom JB, Dubno JR. Level-dependent changes in detection of temporal gaps in noise markers by adults with normal and impaired hearing. *J Acoust Soc Am*. 2011; 130:2928–2938. [PubMed: 22087921]
- Irwin RJ, Ball AKR, Kay N, et al. The development of auditory temporal acuity in children. *Child Dev*. 1985; 56:614–620. [PubMed: 4006570]
- Irwin RJ, Hinchcliffe LK, Kemp S. Temporal acuity in normal and hearing-impaired listeners. *Audiol*. 1981; 20:234–243.
- Jesteadt W, Bacon SP, Lehman JR. Forward masking as a function of frequency, masker level, and signal delay. *J Acoust Soc Am*. 1982; 71:950–962. [PubMed: 7085983]
- Johnson EE, Dillon H. A comparison of gain for adults from generic hearing aid prescriptive methods: Impacts on predicted loudness, frequency bandwidth, and speech intelligibility. *J Am Acad Audiol*. 2011; 22:441–459. [PubMed: 21993050]
- Keidser G, Dillon H, Flax M, et al. The NAL-NL2 prescription procedure. *Audiol Res*. 2011; 1:88–90.
- Levitt H. Transformed up-down methods in psychoacoustics. *J Acoust Soc Am*. 1971; 49:467–477.
- Moore B, Glasberg B. Gap detection with sinusoids and noise in normal, impaired, and electrically stimulated ears. *J Acoust Soc Am*. 1988; 83:1093–1101. [PubMed: 3356814]
- Moore B, Glasberg B, Alcántara J, et al. Effects of slow-and fast-acting compression on the detection of gaps in narrow bands of noise. *Br J Audiol*. 2001; 35:365–374. [PubMed: 11848178]
- Moore B, Glasberg BR, Stone MA. Development of a new method for deriving initial fittings for hearing aids with multi-channel compression: CAMEQ2-HF. *Int J Audiol*. 2010; 49:216–227. [PubMed: 20151930]
- Moore BCJ, Peters R, Glasberg B. Detection of temporal gaps in sinusoids by elderly subjects with and without hearing loss. *J Acoust Soc Am*. 1992; 92:1923–1932. [PubMed: 1401537]
- Penner MJ. Detection of temporal gaps in noise as a measure of the decay of auditory sensation. *J Acoust Soc Am*. 1977; 61:552–557. [PubMed: 845317]
- Plomp R. Rate of decay of auditory sensation. *J Acoust Soc Am*. 1964; 36:277–282.
- Rance G, McKay C, Grayden D. Perceptual characterization of children with auditory neuropathy. *Ear Hear*. 2004; 25:34–46. [PubMed: 14770016]
- Scollie S, Seewald R, Cornelisse L, et al. The desired sensation level multistage input/output algorithm. *Trends Amplif*. 2005; 9:159–197. [PubMed: 16424945]
- Shailer M, Moore B. Gap detection as a function of frequency, bandwidth, and level. *J Acoust Soc Am*. 1983; 74:467–473. [PubMed: 6619424]
- Shannon RV, Zeng FG, Kamath V, et al. Speech recognition with primarily temporal cues. *Science*. 1995; 270:303–304. [PubMed: 7569981]
- Souza PE, Jenstad LM, Boike KT. Measuring the acoustic effects of compression amplification on speech in noise. *J Acoust Soc Am*. 2006; 119:41–44. [PubMed: 16454262]
- Trehub SE, Schneider BA, Henderson JL. Gap detection in infants, children, and adults. *J Acoust Soc Am*. 1995; 98:2532–2541. [PubMed: 7593935]
- Werner L, Marean G, Halpin C, et al. Infant auditory temporal acuity: Gap detection. *Child Dev*. 1992; 63:260–272. [PubMed: 1611932]
- Wightman F, Allen P, Dolan T, et al. Temporal resolution in children. *Child Dev*. 1989; 60:611–624. [PubMed: 2737011]
- Zeng FG, Kong YY, Michalewski HJ, et al. Perceptual consequences of disrupted auditory nerve activity. *J Neurophysiol*. 2005; 93:3050–3063. [PubMed: 15615831]

Figure 1. Output for broadband noise (100 – 8000 Hz) for an adult with sensorineural hearing loss in this study. Desired Sensation Level adult (DSL-A) and child (DSL-C) are shown in the left and right plots, respectively. The dark blue line with the X symbol are the participant's hearing thresholds¹. The solid lines show the output levels¹, from the lowest to highest levels, for noise input levels of 20, 30, 40, 50, 60 and 70 dB SPL.

Figure 2.

Audiometric thresholds of the participants in experiment I. To prevent overlap, the data points are offset from the tested frequency. 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 scores. Overlapping lines are due to the small variance that sometimes occurred.

Figure 3.

Spectrum and waveform plots. Left column shows spectrum plots of the 20-ms gap-duration stimuli (60 dB SPL) for an adult with sensorineural hearing loss in this study (same adult used to generate Figure 1). The first row depicts a noise stimulus without the gap (i.e. standard stimulus) and the second row a noise stimulus with the gap (i.e. target stimulus). Right column plots the waveform of a standard stimulus with fast (top) and slow (bottom) compression. The amplification conditions are labeled above each figure. DSL-C, Child version of the Desired Sensation Level i/o program; Fast, fast compression; slow, slow compression.

Figure 4.

Stimulus-level thresholds for the adult participants (left) and for the child participants (right). To prevent overlap, the data points are offset from the tested gap duration. Error bars represent one standard deviation. DSL-A, Adult version of the Desired Sensation Level i/o program; DSL-C, Child version of the Desired Sensation Level i/o program; NH, normal hearing; SNHL, sensorineural hearing loss.

Figure 5.

Age versus stimulus-level threshold for the children. Each scatterplot is for a different gap duration. None of the correlations were statistically significant. DSL-C, Child version of the Desired Sensation Level i/o program; NH, normal hearing; SNHL, sensorineural hearing loss; r, Pearson correlation.

Figure 6.

Degree of hearing loss versus stimulus-level threshold for the children. Each scatterplot is for a different gap duration. Except for the 5-ms gap duration, pure-tone average was not significantly correlated with stimulus-level thresholds. DSL-C, Child version of the Desired Sensation Level i/o program.

Figure 7. Stimulus-level thresholds for 8 adult subjects with slow and fast compression. To prevent overlap, the data points are offset from the tested gap duration. Error bars show 1 standard deviation.

Figure 8.

Stimulus-level thresholds for this study compared to stimulus-level thresholds for Fitzgibbons et al. (1983) and to gap-duration thresholds for previous studies. Replotted from Figure 4 are the adults with NH. Irwin, Irwin et al. (1981); Florentine, Florentine and Buus (1984); Fitzgibbons, Fitzgibbons et al. (1983); Penner, Penner (1977); Plomp, Plomp (1964).

Table 1

Filterbank center frequencies and 6-dB down points in cycles per second (Hz).

Channel	Lower Cutoff	Center Frequency	Upper Cutoff
1	0	250	360
2	280	400	560
3	420	630	810
4	780	1000	1240
5	1240	1600	1990
6	1990	2500	3160
7	3170	4000	5030
8	5030	6300	11000

Table 2

Participant groups and conditions for each experiment. DSL-C, Child version of the Desired Sensation Level i/o program; DSL-A, Adult version of the Desired Sensation Level i/o program; fast, fast compression (5-ms attack time, 150-ms release time); slow, slow compression (50-ms attack time, 150-ms release time).

Experiment	Participant Groups	Conditions
I	Adults NH	unaided
	Adults SNHL	unaided, DSL-A fast, DSL-C fast
	Children NH	unaided
	Children SNHL	unaided, DSL-C fast
II	Adults SNHL	DSL-C fast, DSL-C slow
III	Adults NH	unaided stimulus-level thresholds, unaided gap-duration thresholds

ANOVA models. The prescriptive procedure model included the adults with SNHL only. The hearing status and age model included the adults and children with and without SNHL. Only the DSL-C data were included in this second model for the participants with SNHL. The compression speed model included the adults from experiment II.

Table 3

Model	Main Effects and Interactions	df	F	p	η^2
Prescriptive Procedure	Gap Duration	1,4,20	64	<0.001 *	0.82
	Prescriptive Procedure	1,14	496	<0.001 *	0.97
Hearing Status and Age	Gap Duration $\times$ Prescriptive Procedure	1,3,32	.513	0.530	0.04
	Gap Duration	2,1,115	106	<0.001 *	0.66
	Age Group	1,54	9	0.005 *	0.14
	Hearing Status	1,54	2	0.131	0.04
	Gap Duration $\times$ Age	2,1,115	2	0.125	0.04
Compression Speed	Gap Duration $\times$ Hearing Status	2,1,115	8	<0.001 *	0.14
	Age $\times$ Hearing Status	1,54	3	0.094	0.05
	Gap Duration $\times$ Age $\times$ Hearing Status	2,1,115	4	0.024 *	0.07
	Gap Duration	1,1,7.5	18.5	0.003 *	0.73
	Compression Speed	1,7	2.2	0.180	0.24
	Gap Duration $\times$ Speed	1,7,12.2	1.5	0.255	0.18

df, degrees of freedom (effect, residuals); F, F-ratio; p, probability value; η^2 , eta squared effect size;
* $p < .05$.

Table 4

Linear mixed model. Only the children were included in this analysis. Data consisted of DSL-C for the children with SNHL.

Fixed effects	Estimate	Standard Error	<i>t</i>	<i>p</i>
Age	−2.66	0.959	−2.78	0.012 [*]
PTA	−0.04	0.236	−0.17	0.864
Age × PTA	0.02	0.021	1.14	0.269

t, *t*-values; *p*, probability values; PTA, pure-tone average;

^{*}
p < .05.

Table 5

The mean, standard deviation (in parenthesis) and t-test of the gap-detection thresholds for each stimulus level. The degrees of freedom were 6 for each t-test.

Gap Duration	Stimulus-Level Threshold	Gap-Duration Threshold	Confidence Interval	<i>t</i>	<i>p</i>
5 ms	33 (5.7)	5.9 (2.1)	4.0 – 7.8	1.20	.274
10 ms	23 (5.2)	11.4 (3.1)	8.5 – 14.3	1.17	.287
15 ms	21 (3.8)	17.8 (4.8)	13.4 – 22.2	1.55	.173
20 ms	18 (4.3)	23.8 (8.2)	16.2 – 31.4	1.23	.265

t-values; *p*: probability values;

* $p < .05$.