Influence of suppression on restoration of spectral loudness summation in listeners with hearing loss

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Loudness depends on both the intensity and spectrum of a sound. Listeners with normal hearing perceive a broadband sound as being louder than an equal-level narrowband sound because loudness grows nonlinearly with level and is then summed across frequency bands. This difference in loudness as a function of bandwidth is reduced in listeners with sensorineural hearing loss (SNHL). Suppression, the reduction in the cochlear response to one sound by the simultaneous presentation of another sound, is also reduced in listeners with SNHL. Hearing-aid gain that is based on loudness measurements with pure tones may fail to restore normal loudness growth for broadband sounds. This study investigated whether hearing-aid amplification that mimics suppression can improve loudness summation for listeners with SNHL. Estimates of loudness summation were obtained using measurements of categorical loudness scaling (CLS). Stimuli were bandpass-filtered noises centered at 2 kHz with bandwidths in the range of 0.1–6.4 kHz. Gain was selected to restore normal loudness based on CLS measurements with pure tones. Gain that accounts for both compression and suppression resulted in better restoration of loudness summation, compared to compression alone. However, restoration was imperfect, suggesting that additional refinements to the signal processing and gain-prescription algorithms are needed. © 2018 Acoustical Society of America.

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I. INTRODUCTION

Current hearing-aid fitting procedures consider loudness in their prescription of gain. For example, the NAL-NL2 aims to amplify speech to maximize a model of speech intelligibility while providing normal loudness (Keidser *et al.*, 2011), and the CAMEQ aims to obtain a flat excitation pattern for speech with equal loudness across frequencies (Moore and Glasberg, 1998). Despite these efforts, dissatisfaction with the percept of loudness still remains one of the factors that influences acceptance of hearing aids by individuals with cochlear hearing loss (e.g., Shi *et al.*, 2007; Blamey and Martin, 2009). Dissatisfaction with loudness perception in realistic listening environments might be related to the fact that hearing-aid fitting procedures are mainly based on measurements with pure tones, and the gain they prescribe is focused on the dependence of loudness on the physical intensity of a sound [i.e., sound pressure level (SPL)]. Even if gain prescriptions are based on the level that restores normal loudness growth, this restoration would be restricted to tonal or narrowband signals, and may not apply to complex signals, because they fail to account for changes in loudness summation as a result of hearing loss (e.g., Garnier *et al.*, 2000; Oetting *et al.*, 2016, 2017). Suppression, the reduction in the cochlear response to one

sound as a consequence of the simultaneous presence of another sound, may influence loudness summation because it describes how the level of one sound affects the level of another sound at a different frequency. The aim of this study was to evaluate whether an experimental hearing aid that was designed to restore both suppression and loudness growth would be effective in restoring loudness summation.

Loudness summation occurs when listeners with normal hearing (NH) perceive a broadband signal as being louder than a narrowband signal when the signals are presented at the same SPL (e.g., Zwicker *et al.*, 1957; Verhey and Kollmeier, 2002). Stated another way, the SPL of a narrowband signal has to be greater than that of a broadband signal for the two signals to be perceived as having the same loudness. The transition between a narrowband and broadband sound that is associated with this phenomenon is known as the *critical* bandwidth (e.g., Fletcher and Munson, 1933). The mechanisms underlying the perception of loudness are not fully understood; however, it is generally believed that loudness is related to the total neural activity that is evoked by a sound (e.g., Moore, 2012).

Loudness summation is reduced when SNHL exists (e.g., Scharf and Hellman, 1966; Florentine and Zwicker, 1979; Garnier *et al.*, 1999; Garnier *et al.*, 2000). Compared to listeners with NH, listeners with SNHL require a greater bandwidth difference between equal-SPL narrowband and broadband signals to perceive a difference in loudness. In

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other words, the level difference between equally-loud narrowband and broadband signals is smaller for listeners with SNHL than for listeners with NH. Reduced loudness summation in listeners with SNHL has been attributed to loss of cochlear compression and broadened auditory filters (e.g., Garnier *et al.*, 2000; Moore and Glasberg, 2004).

Loudness summation is traditionally measured using a loudness-matching procedure, whereby the loudness of a fixed bandwidth stimulus (usually a pure tone) is compared to that of a variable bandwidth stimulus (e.g., Marks and Florentine, 2011; Strelcyk *et al.*, 2012). Categorical loudness scaling (CLS) has also been used to measure loudness summation (e.g., Garnier *et al.*, 1999; Garnier *et al.*, 2000; Anweiler and Verhey, 2006; Oetting *et al.*, 2016, 2017). In this case, loudness matching is performed by equating loudness categories after the data have been collected. A similar loudness-category equating procedure has been used to construct equal loudness contours using data collected with CLS (e.g., Heeren *et al.*, 2013; Rasetshwane *et al.*, 2015). Several studies have shown that CLS measurements are reliable and the patterns of CLS data are predictable from what is known about the consequences of hearing loss (Robinson and Gatehouse, 1996; Cox *et al.*, 1997; Rasmussen *et al.*, 1998; Al-Salim *et al.*, 2010; Rasetshwane *et al.*, 2015). In addition, compared to traditional loudness measures, CLS has the advantage that it relates to a listener's experience and informal descriptions of his or her loudness percepts, requires minimal training, and requires an amount of time that might be acceptable clinically. Consequently, we chose to use CLS for our measurement of loudness summation.

Two-tone suppression refers to a reduction in the response growth of one tone in the presence of a second tone. For a stimulus with multiple frequency components, such as speech, suppression may be interpreted as providing a description of how these components interact in the cochlea. Suppression has been shown to play a role in the processing of broadband and complex sounds (e.g., Houtgast, 1974; Sachs and Young, 1980). Suppression is linked to the same underlying mechanism responsible for cochlear compression. Like loudness summation, both compression and suppression are reduced in listeners with SNHL. A hearing-aid signal processing approach that restores suppression, in addition to compression, may be more successful in restoring normal loudness summation (compared to processing schemes that ignore suppressive effects) because suppression describes how different frequency components interact. In turn, incorporating suppression into hearing-aid signal-processing strategies may lead to better hearing-aid performance and benefit.

We previously described a hearing-aid signal-processing algorithm that mimics the effects of normal cochlear suppression, which we referred to as the suppression hearing aid (SHA) (Rasetshwane *et al.*, 2014b). The suppressive influence of one frequency on another frequency in the SHA is based on measurements of distortion-product otoacoustic emission (DPOAE) suppression tuning curves in humans with NH (Gorga *et al.*, 2011a). For evaluation purposes, a compression-only hearing aid (CHA) can be realized by

disabling the suppression of the SHA, while other functionalities remain unchanged.

The goal of the fitting strategy for the SHA (and the CHA) was to provide frequency and level-dependent gain that restores normal loudness growth for both narrowband and broadband signals. Specifically, the strategy aimed to provide gain such that loudness ratings provided by an individual with SNHL matched loudness ratings provided by individuals with NH. The idea of providing hearing-aid amplification that restores normal loudness perception for listeners with hearing loss has been explored by several researchers (e.g., Allen *et al.*, 1990; Kollmeier *et al.*, 1993; Cox, 1995; Rasetshwane *et al.*, 2015; Oetting *et al.*, 2016).

In the current study, we evaluate whether an approach that combines efforts to restore both loudness and suppression would be effective in restoring loudness summation. Hearing-aid amplification that is based on narrowband signals results in excessive gain and uncomfortable loudness for broadband signals because of loudness summation (e.g., Strelcyk *et al.*, 2012; Oetting *et al.*, 2016, 2017). A "correction factor" to the gain prescription that is based on narrowband stimuli is required in order to account for loudness summation and avoid uncomfortable loudness when listening to broadband sounds at high levels. Widely used gain prescription algorithms, NAL-NL2 (Keidser *et al.*, 2012) and DSL (Scollie *et al.*, 2005), include such correction factors; however, these are empirical and their underlying mechanism are not well understood. The current study, in essence, evaluated whether suppression can be the correction factor that accounts for loudness summation.

Strelcyk *et al.* (2012) proposed a hearing-aid algorithm for restoring loudness summation that utilized level-dependent channel bandwidth, i.e., channels widening with increasing level, and obtained promising results. We extend this previous effort, of which the design was empirical, by basing the design of our signal-processing algorithm on measurements of suppression and loudness from humans, which provides greater ecological validity.

Oetting *et al.* (2016) measured loudness growth and loudness summation for listeners with NH and SNHL using CLS. Amplification to restore narrowband loudness was provided for listeners with SNHL. Oetting *et al.* demonstrated good agreement between average loudness functions for listeners with NH and SNHL for monaural broadband signals. However, the gain based on narrowband signals was excessive when listening to broadband signals at high SPL: the majority of their listeners with SNHL required a lower level in order to rate the broadband signal as having the same loudness as a narrowband signal.

In a follow up study, Oetting *et al.* (2017) described a bandwidth-adaptive dynamic range compressor in which different gains were applied for narrowband and broadband signals depending on the listener's deviation from the average normal-hearing loudness functions. Similar to their earlier study, Oetting *et al.* (2017) demonstrated that gain that was based on narrowband signals was excessive for broadband signals. Additionally, they demonstrated that the gain correction required to restore loudness for broadband signals varied greatly across listeners, suggesting that loudness

compensation for narrowband and broadband stimuli cannot be achieved by compression algorithms that do not consider loudness summation.

The specific goals of this study were to determine the effect of hearing-aid amplification on loudness summation and evaluate whether hearing-aid amplification that restores suppression and loudness growth also restores loudness summation. Our use of CLS to estimate loudness summation extends previous studies by obtaining measurements under conditions of hearing-aid amplification and in a large number of participants. We determined the effect of hearing-aid amplification on loudness summation, and loudness in general, by comparing estimates of unaided and aided loudness summation. Finally, we determined the effect of incorporating suppression in a dynamic-range compression hearing aid by comparing estimates of loudness summation obtained with the SHA to those obtained with the CHA. Data from participants with NH provide references for normal loudness summation.

II. METHODS

A. Participants

Seventy-three participants took part in this study, and met the inclusion criteria described. There were 20 (13 female) participants with NH [mean age = 40, standard deviation (SD) = 13, range = 20–66 years] and 53 (31 female) participants with SNHL (mean age = 65, SD = 7, range = 43–80 years). Pure-tone air-conduction audiometric thresholds were measured at octave frequencies (0.25, 0.5, 1, 2, 4, and 8 kHz), while bone-conduction thresholds were measured at octave frequencies from 0.25 to 4 kHz. Additional air-conduction thresholds were measured at inter-octave frequencies (0.75, 1.5, 3, and 6 kHz) in participants with SNHL. Thresholds were measured in 5-dB steps, following standard clinical procedures. Participants with air-conduction thresholds ≤ 15 dB hearing level (HL) at all frequencies were considered to have NH. Participants with thresholds > 15 dB HL at one or more test frequencies were considered to have SNHL. Participants were excluded from the study if air-bone gaps were > 10 dB at any frequency, suggesting conductive hearing loss rather than SNHL. Participants with SNHL were categorized into two groups, mild and moderate SNHL, based on the pure-tone threshold average (PTA) at 2, 3, and 4 kHz. The mild SNHL group had PTA of 20–40 dB and the moderate SNHL group had PTA of 45–65 dB. Of the 53 participants with SNHL, there were 25 participants (19 females) in the mild SNHL group and 28 (12 females) in the moderate SNHL group. Participants were excluded if they were unable to perform the loudness-rating task, whether due to difficulty understanding the task or because tinnitus precluded them from making reliable judgments at high frequencies. This study was conducted under an approved Institutional Review Board protocol and informed consent was obtained from all participants. Figure 1 shows the audiometric thresholds for the three groups of participants.

Data were collected for only one ear per participant. If both ears met the inclusion criteria, and there was a

FIG. 1. (Color online) Audiometric thresholds for the three groups of participants included in the study (see figure legend). The region shaded shows the inter-quartile range and the thick solid line within each region shows the mean.

difference in hearing sensitivity between ears, the ear with better hearing was selected for testing. If the two ears had similar audiometric thresholds, the test ear was selected randomly. Data were collected from 11 right and 9 left ears with NH, 17 right and 8 left ears with mild SNHL, and 16 right and 12 left ears with moderate SNHL.

B. Equipment

A 24-bit sound card (Babyface, RME, Germany) was used to generate the stimuli. The stimuli were presented unilaterally to the participant's test ear with a headphone (HD-25-1 II, Sennheiser, Ireland). The frequency response of the headphone was measured using a sound-level meter (System 824; Larson Davis, Provo, UT) and used to derive a SPL correction for ear-canal acoustics. The headphone was coupled to the sound level meter using a Larson Davis model AEC 100 coupler. Additionally, a correction for the acoustics of the pinna and ear canal was determined from measurements made using KEMAR (G.R.A.S. Sound and Vibration A/S, Denmark) and a sound-level meter. These two corrections were combined to derive a free field to eardrum correction function that was subsequently applied to the CLS measurements. Although this correction is not a true free-field correction (e.g., Shaw, 1965), it accounts for most of the frequency response-shaping propagation path of the stimulus, missing only the propagation from external loudspeaker to pinna. This correction facilitates comparison of our loudness measurements to other loudness measurements that were made with a free-field sound source. MATLAB software (Natick, MA) was used to control stimulus delivery and to record the responses of the participants.

C. Measurements and stimuli

The CLS procedure determined the level of sounds that corresponded to different loudness categories using an adaptive procedure (Brand and Hohmann, 2002; ISO 16832,

2006; Al-Salim *et al.*, 2010). A total of 11 loudness categories were used, with seven of these categories assigned meaningful labels (“can’t hear,” “very soft,” “soft,” “medium,” “loud,” “very loud,” and “too loud”). The categories were displayed on a computer monitor using colored horizontal bars with increasing length from the softest to the loudest descriptor (see Fig. 1 of Rasetshwane *et al.*, 2015 for an example of the colored response scale). For the purpose of numerical representation, the 11 loudness categories were assigned categorical units (CU) ranging from 0 (cannot hear) to 50 (too loud) in steps of 5. However, the numerical scale was not displayed on the response scale used by the participants. The labels used at the boundary categories, “can’t hear” and “too loud,” are the same as those used in Rasetshwane *et al.* (2015), but different from those used in the ISO 16832 standard. The ISO recommends “not heard” and “extremely loud.” The difference in the labels does not have an effect on the data, as was demonstrated by Rasetshwane *et al.* (2015). Additionally, it is worthwhile to note that the ISO 16832 is open to the use of different labels for the categories, including symbols. Participants used a computer mouse to click on the category that best matched their loudness perception. Participants were encouraged to use both labeled and unlabeled bars. The CLS procedure included two stages. In the first stage, the dynamic range of the participant was determined by presenting two sequences of stimuli, one sequence ascending in level and the other descending in level. The lower end of a participant’s dynamic range was based on the last audible level of the descending sequence, while the upper end was based on the last level of the ascending sequence that was not judged as “too loud.” In the second stage, stimuli were presented at 18 levels within the participant’s dynamic range. The participant was asked to rate the loudness of the stimuli using loudness categories, as described above. The second stage of the CLS procedure was repeated three times, with the dynamic range adjusted and the stimulus level re-determined for each subsequent repetition based on the responses of the participant. Thus, there were 54 trials in the second stage. In the first set of trials, the 18 levels were equally spaced within the participant’s dynamic range. In the second and third sets, the 18 levels were distributed between the levels required for loudness categories of 5 and 45 CU in the previous set. These levels were determined by fitting a model loudness function such that the levels for $CU \leq 25$ were equally spaced, and the levels for $CU \geq 25$ were equally spaced. The order of presentation of the stimulus levels within each of the three sets was randomized. The starting presentation level was fixed at 60 dB SPL for participants with NH. For participants with SNHL, the starting level was half way between their audiometric threshold and the maximum presentation level at a given frequency. The maximum presentation level was set at 110 dB SPL to avoid loudness discomfort.

CLS measurements for the purposes of the hearing-aid fitting were made using pure tones at the same frequencies at which audiometric thresholds were measured. Following Anweiler and Verhey (2006), CLS measurements for estimation of loudness summation were made using bandpass-

filtered noise stimuli with a center frequency of 2 kHz and geometrically centered bandwidths of 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, and 6.4 kHz. Both pure-tone and noise stimuli were 1000 ms in duration with rise/fall times of 20 ms. Data collection at a single frequency/bandwidth took approximately 5 min to complete and followed identical procedures. Pure-tone CLS measurements were only obtained in participants with SNHL. All participants were given a practice run using a pure tone at 1.25 kHz. For each participant, the order of presentation of the tones, as well as that of the noise bandwidths, was randomized. CLS measurements were made monaurally and separately for each noise bandwidth and pure-tone frequency.

D. Suppression hearing aid

Brief descriptions of the signal processing and gain prescription algorithms are provided below. Please see Rasetshwane *et al.* (2014b) for a more detailed description of the SHA.

1. Signal processing

The SHA signal-processing algorithm includes three stages: analysis, suppression and synthesis. The analysis stage uses a complex Gammatone filterbank to decompose the input signal into 31 channels that span the frequency range up to 12 kHz (Hohmann, 2002). The outputs of the filterbank are complex signals, which allow calculation of the instantaneous time-domain level. Filters below 1 kHz were designed to have a constant equivalent rectangular bandwidth (ERB) of 0.1 kHz and linearly spaced center frequencies (f_c) with 0.1-kHz steps. The filter at 1 kHz had an ERB of 0.11 kHz. Filters above 1 kHz had constant tuning ($Q_{\text{ERB}} = 8.65$) and center frequencies that were logarithmically spaced with $\frac{1}{6}$ -octave steps. Q_{ERB} is defined as $f_c/\text{ERB}(f_c)$ and $\text{ERB}(f_c)$ is the equivalent rectangular bandwidth of a filter with center frequency f_c . This tuning resulted in a filterbank delay that varied by approximately 4 ms across frequency, which is within limits that are acceptable to hearing-aid users (Stone *et al.*, 2008).

The SHA provides instantaneous compression with gain that implements two-tone suppression. The suppressive influence of one frequency on another frequency was based on measurements of DPOAE suppression tuning curves (STCs) in humans with NH (Gorga *et al.*, 2011a). In these experiments, DPOAEs were elicited by a pair of primary tones (f_1 and f_2), whose levels were held constant while a third tone (f_3) was presented as a suppressor (e.g., Gorga *et al.*, 2011a,b). The effect of the suppressor tone was defined as the amount by which its presence reduced the DPOAE level in response to the primary tones. This suppressive effect was characterized for a range of levels and frequencies of both the suppressor and primary tones. The gain applied to a particular frequency band in the SHA is based on the instantaneous level of every filterbank output in a manner based on measurements of DPOAE STCs. However, unlike in DPOAE suppression measurements where the suppressive effect of a suppressor frequency (f_3) on the DPOAE level in response to two primary tones (f_1 and f_2) was

represented, the SHA signal processing represents the influence of a suppressor frequency (f_s) which is equivalent to f_3 on a probe frequency (f_p) which is equivalent to (f_2). The suppressive effect was extended to multiple suppressors by assuming that suppression is additive in the intensity domain. This assumption is a simplification and might not describe the ways in which suppressive effects add for all stimulus conditions (see [Sieck et al., 2016](#)). Suppose that the total suppressive influence on a tone at f of multiple suppressor tones at f_j can be described by summing the individual suppressive intensities of each tone:

$$L_s(f) = 10 \log_{10} \left(\sum_{j=1}^N 10^{S_j(f)/10} \right), \quad (1)$$

where

$$S_j(f) = c_1(f, f_j) + c_2(f, f_j)L_j \quad (2)$$

represents the individual suppressive level on a tone at f of a single suppressor tone at f_j , and L_j is the filter output level at f_j . Subscript j is the channel index. The “total suppressive influence” [Eq. (1)] combines the suppressive effect of all frequency components into a single, equivalent level L_s that would cause the same reduction in gain (due to compression) if it was the level of a single tone. Coefficients c_1 and c_2 are derived from the DPOAE data. The output level of each channel was limited to 110 dB SPL. In addition to this channel limit, a limit of 110 dB SPL was imposed on the output of the hearing aid.

Last, the synthesis stage combined the output of the 31 channels included in the suppressor stage, producing an output signal with suppressive influences. For comparison purposes, suppression can be disabled while the other functionalities remain unchanged, resulting in a compression-only hearing aid (CHA).

The ability of the SHA to mimic suppressive effects is demonstrated in Fig. 2, in which DPOAE STC for $f_2 = 1, 2, 4$, and 8 kHz from [Gorga et al. \(2011a\)](#) are compared to the output of the SHA for f_p at the same frequencies. In the DPOAE study, the level of f_2 (i.e., L_2) ranged from 10 dB sensation level (SL) (lowest STC) to 60 dB SL (highest STC) in 10-dB steps. The level of f_1 (L_1) was determined empirically and individually, using a paradigm in which both L_1 and L_2 were continuously varied, resulting in a Lissajous pattern of DPOAE level (see [Neely et al., 2005](#) for a description of the Lissajous procedure). For each combination of f_2 and L_2 , the suppressor frequency (f_3) was varied from about 1 or 2 octaves below f_2 to about $\frac{1}{4}$ or $\frac{1}{2}$ octave above f_2 . STCs represent the level of the suppressor L_3 at the suppression threshold (which was defined as a 3-dB reduction in the DPOAE level caused by the suppressor tone). Parameter values for the SHA signal processing were selected to match corresponding values for DPOAE STCs. Specifically, suppression threshold for the SHA was defined as the level of the suppressor that resulted in a 3-dB reduction in the level of the probe. Figure 2 shows that the STCs produced by the SHA (bottom panel) are qualitatively similar to measurements of DPOAE

FIG. 2. (Color online) Comparison of measurements of DPOAE STCs of [Gorga et al. \(2011a,b\)](#); top) to the SHA simulation of STCs (bottom). STCs are shown for $f_2 = 1$ (circles), 2 (triangles), 4 (hourglasses), and 8 kHz (stars). The unconnected symbols below each set of STCs in the top panel represent the mean behavioral thresholds for the group of participants contributing data at that frequency. Adapted from [Gorga et al. \(2011a,b\)](#), [Rasetshwane et al. \(2014b\)](#), and [Rasetshwane et al. \(2018\)](#).

STCs of [Gorga et al. \(2011a\)](#); top panel). The SHA STCs are similar to the DPOAE STCs in both their absolute level and their dependence on probe-tone level.

2. Gain prescription

Gain prescription to restore normal loudness growth utilized CLS measurements with pure-tone stimuli, and was based on the strategy described by [Rasetshwane et al. \(2014b\)](#) and [Rasetshwane et al. \(2015\)](#). In this strategy, average CLS data for listeners with NH provide reference input levels for a given loudness category at each frequency. The gain required for an individual with SNHL is the difference between the normal-reference input level and the input level required by that individual to elicit the same loudness percept. Average CLS data for listeners with NH were based on previous data from 30 participants ([Rasetshwane et al., 2014a](#)). The gain prescription of [Rasetshwane et al. \(2014b\)](#) utilized two loudness categories—“very soft” and “very loud”—as knee-points, and a linear fit between these categories. However, a two-segment linear fit provides a better description of categorical loudness growth (see, for example, [Brand and Hohmann, 2002](#); [Al-Salim et al., 2010](#)). [Rasetshwane et al. \(2015\)](#) demonstrated how the gain prescription can be extended to multiple loudness categories. Therefore, in order to improve the gain prescription, we

expanded the gain function to utilize three knee points, occurring at loudness categories of “very soft,” “medium,” and “very loud.” Including the loudness category of “medium” allowed us to capture the inflexion point of the two-segment loudness growth function. Linear gain was applied below the knee-point corresponding to “very soft,” and above the knee point corresponding to “very loud.” Compressive gain was applied between these two knee-points, utilizing two different compression ratios (CRs). CR_{SM} was used for levels between “very soft” and “medium,” and CR_{ML} and was used for levels between “medium” and “very loud.” Calculations of gain were performed separately for each frequency. Thus, the resulting gain was both frequency and level dependent.

CLS data for participants with SNHL were collected unaided, and with the SHA and with the CHA.

E. Data analysis

1. Hearing-aid gain

To assess the gain characteristics of the hearing-aid simulators, input/output (I/O) functions for the CHA and the SHA were estimated by presenting the bandpass-filtered noise stimuli used for the loudness measurements to the hearing-aid simulators. The input level was varied from 0 to 110 dB SPL in 2-dB steps, and the output level was recorded. I/O functions were created for each individual participant using their CLS-derived gain prescription.

2. Loudness

For each participant, for each bandwidth, and for each processing condition (unaided, SHA, and CHA), CLS data were analyzed to obtain a CLS function (i.e., loudness in CU as a function of dB SPL). The CLS-function analysis followed previously described procedures (Al-Salim *et al.*, 2010; Rasetshwane *et al.*, 2013; Rasetshwane *et al.*, 2015). Briefly, outliers were removed, the median SPL for each CU was calculated, and then a model loudness function was fit to the median data. The model loudness function consisted of two linear functions with independent slopes, one for the portion of the data from 5 to 25 CU and the other for the portion from 25 to 45 CU, similar to Al-Salim *et al.* (2010) and Brand and Hohmann (2002). As in the studies cited above, data for 0 CU (cannot hear) and 50 CU (too loud) were not used in the fit because the SPLs for these categories were unbounded in the sense that a decrease in the stimulus level below threshold by any amount will still result in a rating of “can’t hear,” and an increase in the stimulus level by any amount above the level that was rated “too loud” would still result in a rating of “too loud.” All subsequent analyses were performed on the fitted CLS function. In order to assess the role of amplification on loudness, *deviation from normal loudness* was defined as the level required by a participant with SNHL minus the mean level required by participants with NH to achieve equal loudness (i.e., the same CU).

3. Loudness summation

An estimate of loudness summation was obtained for each participant and for each processing condition in two

steps. First, signal levels for different bandwidths that were perceived as equally loud for each of nine loudness categories (i.e., 5 CU to 45 CU) were plotted. This results in nine stimulus-level versus bandwidth functions. Second, an estimate of the amount of loudness summation was obtained as the slope of these functions. The slope (dB/octave) was calculated by fitting the stimulus-level versus log-bandwidth data with a simple linear regression. This procedure will be described further in Sec. III when results are presented. In order to assess the role of amplification on loudness summation, *deviation from normal loudness summation* was defined for each participant with SNHL as the mean loudness summation for participants with NH minus the loudness summation for the participant with SNHL, with the data matched by loudness category (CU).

4. Statistical analysis

Repeated-measures analysis of variance (ANOVA) was used to determine the influences of between-subject factor, Group (2 levels: mild SNHL and moderate SNHL) and two within-subject factors, Processing (3 levels: unaided, SHA and CHA), and CU (3 levels: 5, 25 and 45) on deviation from normal loudness and deviation from normal loudness summation. For the deviation from normal loudness analysis, an additional within-subject factor, Bandwidth (7 levels: 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, and 6.4 kHz), was included. An unstructured covariance matrix was utilized to analyze the correlated data due to combinations of Processing and CU (and Bandwidth for the deviation from normal loudness analysis) from the same participant in each hearing loss group. Least-square means were used to assess whether the deviation from normal loudness and the deviation from normal loudness summation were different from zero. All statistical analyses were performed using SAS/STAT software, v.9.4 (Cary, NC).

III. RESULTS

A. Hearing-aid gain

The compression ratio prescribed by the CLS gain prescription algorithm depends on frequency, and thus is different for each of the 31 channels of the hearing-aid simulator. To provide a sense of the value of the compression ratio, mean compression ratios across participants are plotted in Fig. 3 for a channel centered at 2 kHz—the center frequency of the noise signals, and for channels centered one octave below and above 2 kHz (i.e., 1 and 4 kHz). Compression ratios CR_{SM} (squares) and CR_{ML} (circles) are plotted separately for participants with mild SNHL (open symbols), and for participants with moderate SNHL (closed symbols). The error bars represent ± 1 standard error (SE). For both groups of participants, CR_{SM} is greater than CR_{ML} , both CR_{SM} and CR_{ML} increase with frequency, with CR_{SM} having a stronger frequency dependence. The increase in compression ratios with frequency is because the participants had high-frequency hearing loss. As expected, greater wide-dynamic range compression was applied for participants with greater degree of hearing loss.

FIG. 3. (Color online) Mean prescribed compression ratios CR_{SM} (squares) and CR_{ML} (circles) for participants with mild SNHL (open symbols), and for participants with moderate SNHL (closed symbols). Compression ratios are plotted for channels centered at 2 (center frequency of the noise signals) and for channels centered at 1 and 4 kHz. Error bars indicate ± 1 SE. CR_{SM} was used for levels between “very soft” and “medium,” and CR_{ML} was used for levels between “medium” and “very loud.”

Figure 4 shows I/O functions for noise signals of different bandwidths. Data are shown for participants with mild SNHL (A) and for participants with moderate SNHL (B), with I/O functions for the CHA plotted using solid lines and those for the SHA plotted using dashed lines. The I/O functions for both the CHA and the SHA have a slope of unity at low levels (below the knee point corresponding to “very soft”) and at high levels (above the knee point corresponding to “very loud”), where linear gain was applied. The I/O functions are compressive at moderate levels. As expected, the output level for participants with moderate SNHL is higher than the output level for participants with mild SNHL, as higher gain was applied for the former group. At moderate and high levels, the output level for the CHA is higher than the output level for the SHA despite the fact that the gains prescribed by the CLS gain-prescription method were identical. This is because, in order to represent suppressive effects, the SHA turned down the gain in a manner that depends on the frequency content of the input signal, as described in Sec. II. This reduction in gain also results in a reduction in the effective compression ratio.

Figure 4 also shows the difference between the gain for the CHA and the gain for the SHA for participants with mild SNHL (C) and for participants with moderate SNHL (D). There is no difference in the gains below 40 dB SPL. Above 40 dB SPL, the gain for the CHA is generally greater than the gain for the SHA. The gain difference increases with bandwidth, and is as large as 12.4 dB for the 6.4 kHz bandwidth noise for participants with moderate SNHL.

B. CLS functions

Figure 5 shows median CLS functions for the three groups of participants. The top panel shows functions for

FIG. 4. (Color online) I/O functions for noise signals of different bandwidth [see legend in panel (C)] for participants with mild SNHL (A) and for participants with moderate SNHL (B). I/O functions for the CHA are plotted using solid lines and those for the SHA are plotted using dashed lines. The difference in gain between the CHA and the SHA are shown in panel (C) for participants with mild SNHL and panel (D) for participants with moderate SNHL. The dotted lines denote gain of zero.

participants with NH, which were collected unaided. The middle row shows data for participants with mild SNHL, and the bottom row shows data for participants with moderate SNHL. The parameter within each panel is bandwidth of the noise, as indicated on the inset (right panel, middle row). The left column shows unaided CLS functions for all participant groups, including participants with NH. The middle and right columns show CLS functions obtained using the SHA and the CHA, respectively, for the two groups with SNHL. For participants with SNHL, level on the abscissa refers to input level before amplification. Comparing the unaided data, the CLS functions for participants with SNHL are shifted to the right (i.e., the level required for 5 CU occurs at higher levels) and have a steeper slope for $CU \leq 25$, compared to functions for participants with NH. Additionally, the slope for the functions for the moderate SNHL group is steeper than that for the mild SNHL group, indicating loudness recruitment. This pattern is consistent with previous measures of CLS (e.g., Brand and Hohmann, 2001; Al-Salim *et al.*, 2010; Rasetshwane *et al.*, 2015). With amplification (middle and right columns), the CLS functions for participants with SNHL look more like those for participants with NH, with less-steep slopes for $CU \leq 25$ and with the level for 5 CU occurring at lower level, compared to unaided conditions.

To provide a sense of the variability in the CLS data, Fig. 6 shows the interquartile range (IQR) and the 5th to 95th percentile range of CLS functions for narrow (0.1 kHz), intermediate (0.8 kHz), and broad (6.4 kHz) signal bandwidths. The median CLS functions are shown using solid

FIG. 5. (Color online) Median CLS functions. The top panel shows data for participants with NH, which were collected unaided. The middle row shows data for participants with mild SNHL, and the bottom row shows data for participants with moderate SNHL. CLS functions for the participants with SNHL are shown for the unaided condition (left column), after SHA amplification (middle column), and after CHA amplification (right column). The parameter within each panel is bandwidth, as indicated by the inset on the right panel in the middle row.

lines. Data for participants with NH are shown in the first column. The remaining columns show data for participants with moderate SNHL for unaided, SHA and CHA conditions. Data for participants with mild SNHL are not shown here but the variability in the data for this group of participants is similar to that for the data for participants with NH and moderate SNHL. In general, variability did not depend on signal bandwidth (compare different rows). The reason for the large variability for participants with NH for soft loudness for the 0.1-kHz bandwidth (upper left panel) is unknown. It is possible that envelope fluctuations in the 0.1-kHz noise contributed to this large variability. Variability also did not depend on processing condition (compare different columns). Additionally, variability did not depend on the degree of hearing loss—the IQR for CLS functions for participants with NH (first column) were similar to the IQR for participants with moderate SNHL (second through fourth column) and participants with mild SNHL (not plotted). The variability in the current data (IQR varied from 7 to 26 dB) is similar to what has been observed in previously reported CLS data for tonal stimuli (e.g., Heeren *et al.*, 2013; ISO, 2006; Rasetshwane *et al.*, 2015). Heeren *et al.* reported CLS functions with an IQR that varied from approximately 20 to 26 dB, and the IQR for ISO 16832 varied from approximately 20 to 28 dB for pure tone stimuli at 1 kHz. IQR from our earlier study varied from 3 to 21 dB. The IQRs reported for ISO (2006) and Heeren *et al.* (2013) are approximations obtained by digitization of figures in these papers.

Figure 7 shows the mean deviation from normal loudness for participants with mild SNHL (top row) and moderate SNHL (bottom row), calculated from the CLS functions that were obtained using noise stimuli (see Fig. 5). The deviation from normal loudness was defined as the level required by participants with SNHL minus the mean level required by participants with NH to achieve equal loudness (CU). The deviation from normal loudness was calculated separately for each participant with SNHL. Data for the seven bandwidths are shown in different columns, with increasing bandwidth from left to right. Within each panel, mean deviations from normal loudness are plotted for the unaided (thin dashed line), the SHA (solid line), and the CHA (thick dashed line) conditions. In the unaided condition, the deviations can be interpreted as representing the gain required to restore normal loudness. For the aided conditions, the deviation from normal loudness can be interpreted as representing the average “gain error.” A “gain error” < 0 dB (above the dotted line at 0 dB) indicates that too much gain was applied. A “gain error” > 0 dB (below the dotted line) indicates that too little gain was applied.

As expected, the gain needed to restore normal loudness for participants with moderate SNHL (bottom row) was greater than the gain needed for participants with mild SNHL (top row). As expected, the deviation from normal loudness for the unaided condition for both groups of participants with SNHL was greater at lower stimulus levels (low CU), and became close to zero at high levels (high CU). This reflects loudness recruitment, and is consistent with

FIG. 6. Variability of CLS functions. As an example, CLS functions are shown for signal bandwidths of 0.1 kHz (top row), 0.8 kHz (middle row), and 6.4 kHz (bottom row). Lighter shading indicates 5th to 95th percentile range and darker shading indicates 25th to 75th percentile (interquartile) range, as shown in the legend in the top left panel. Data for participants with NH, which were collected unaided, are plotted on the first column. The remaining columns show data for participants with moderate SNHL for unaided (second column), SHA (third column) and CHA (fourth column) conditions.

previous demonstrations of recruitment (e.g., [Steinberg and Gardner, 1937](#); [Stevens and Guirao, 1967](#); [Scharf, 1978](#); [Hellman and Meiselman, 1993](#); [Rasetshwane *et al.*, 2015](#)). There is a general pattern across bandwidth in the deviations from normal loudness for both the SHA and the CHA, and

for both groups of participants. The deviations were close to zero at 5 CU, increased with loudness category, peaked at about 20–25 CU, and then decreased towards 45 CU. However, this pattern did not hold for some bandwidths (e.g., 6.4 kHz), where the deviation remained constant or

FIG. 7. (Color online) Deviation from normal loudness, defined as the level required by participants with SNHL minus the average level required by participants with NH for equal loudness. The top and bottom rows show data for participants with mild SNHL and moderate SNHL, respectively. Data for the seven bandwidths of the noise signals are shown in different columns (see top labels). Data are shown for the unaided (thin dashed line), SHA (solid line), and CHA (thick dashed line) conditions.

increased at high CUs. There was a gain error <0 dB for most CUs and bandwidths for both the SHA and the CHA for both groups of participants, indicating that too much gain was applied.

The results of the repeated measures ANOVA of deviation from normal loudness are presented in Table I. All the four main effects (Group, Processing, CU, and Bandwidth) were statistically significant. All the two-way interactions were statistically significant, except Group $\times$ CU. All the three-way interactions were statistically significant, except Group $\times$ Processing $\times$ Bandwidth. The four-way interaction Group $\times$ Processing $\times$ CU $\times$ Bandwidth was also statistically significant.

Because the four-way interaction was statistically significant, the simple effects of Group, Processing, CU, and Bandwidth were examined using least-square means at combinations of the other three variables. 95% CIs for the least-square means were calculated. CIs that do not include zero indicate that the deviations from normal loudness were statistically significant at a p-value of 0.05. Because of the vast number of conditions, we simplify the interpretation of the results by highlighting the conditions (combination of Group $\times$ Processing $\times$ CU) for which statistically significant deviations were observed for more than one bandwidth. The complete table of least-square means and their 95% CIs are available in the supplementary material¹.

For the mild SNHL group, the analysis indicated that statistically significant deviations from normal loudness were observed in the unaided condition at 5 CU for all seven

bandwidths. Following amplification, statistically significant deviations were observed at 25 CU for five bandwidths and at 45 CUs for two bandwidths for the SHA. For the CHA, statistically significant deviations were observed at 25 CU for 5 bandwidths, and at 45 CU for three bandwidths. No other conditions had statistically significant deviations for more than one bandwidth. In summary, both SHA and CHA restored normal loudness for the mild SNHL group for soft sounds (5 CU), but provided excess gain and resulted in above normal loudness for medium loudness sounds (25 CU) for most bandwidths. SHA and CHA provided excess gain for loud sounds (45 CU) only for a few bandwidths.

For the moderate SNHL group, statistically significant deviations from normal loudness were observed in the unaided condition at all CUs: seven bandwidths at 5 CU, six bandwidths at 25 CU, and four bandwidths at 45 CU. Following amplification, statistically significant deviations were observed at 25 CU for three bandwidths for the SHA. For the CHA, statistically significant deviations were observed at 25 CU for all seven bandwidths. No other conditions had statistically significant deviations for more than one bandwidth. In summary, both SHA and CHA restored normal loudness for the moderate SNHL group for soft and loud sounds. However, both processing strategies provided excessive gain for medium sounds, with the CHA over-amplifying all seven bandwidths, and the SHA over-amplifying only 3 bandwidths.

C. Loudness summation

To provide a demonstration of loudness summation, Fig. 8 shows stimulus level as a function of bandwidth for all nine loudness categories for participants with NH. The symbols represent mean data and the solid lines are simple linear regression fits to the data. The error bars represent ± 1 SE. Each function is an equal-loudness function of bandwidth. Data for bandwidths of 0.1, 0.2, and 6.4 kHz were not included in the calculation of the regression lines. Bandwidths of 0.1 and 0.2 kHz are within the critical band at 2 kHz (Zwicker *et al.*, 1957; Glasberg and Moore, 1990), and thus were not expected to differ in loudness. According to Glasberg and Moore (1990), the critical bandwidth for a listener with normal hearing is 0.24 kHz for a center frequency of 2 kHz at moderate presentation level (40–50) dB SPL. Data for the 6.4-kHz bandwidth deviated strongly and consistently from the trends for smaller bandwidths up to 3.2 kHz. It is likely that factors other than loudness summation are involved in the 6.4-kHz bandwidth. The level required for equal loudness decreases as bandwidth increases for loudness categories of 5 to 35 CU. That is, a higher SPL is required for narrowband signals compared to broadband signals in order to maintain equal loudness. Regression lines associated with these loudness categories had negative slope, with the largest negative slope occurring at 20 CU. The slopes for functions for loudness categories of 40 and 45 CU were positive but close to zero. We use the slopes of the regression lines as estimates of the amount of loudness summation, with a steeper negative slope indicating a greater amount of loudness summation. A negative slope indicates

TABLE I. Analysis of variance for repeated measures of deviation from normal loudness for participants with SNHL. The deviation from normal loudness was defined as the level required by a participant with SNHL minus the mean level required by participants with NH to achieve equal loudness (CU). Main effects were Group (2 levels: mild SNHL and moderate SNHL), Processing (3 levels: unaided, SHA, and CHA), CU (3 levels: 5, 25, and 45), and Bandwidth (7 levels: 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, and 6.4 kHz). Processing, CU, and Bandwidth are repeated measures factors within each participant. DF denotes degrees of freedom for the denominator.

Effect	DF	F value	p value	η^2	ω^2
Group	250.7	11.67	<0.001 ^a	0.002	0.002
Processing	194.0	68.83	<0.001 ^a	0.028	0.028
Group $\times$ Processing	194.0	9.60	<0.001 ^a	0.004	0.004
CU	212.5	51.34	<0.001 ^a	0.021	0.021
Group $\times$ CU	212.5	0.53	0.590	0	0
Processing $\times$ CU	177.3	18.43	<0.001 ^a	0.015	0.014
Group $\times$ Processing $\times$ CU	177.3	3.38	0.011 ^b	0.003	0.002
Bandwidth	311.3	8.99	<0.001 ^a	0.011	0.010
Group $\times$ Bandwidth	311.3	1.67	0.130	0.002	0.001
Processing $\times$ Bandwidth	513.6	2.96	<0.001 ^a	0.007	0.005
Group $\times$ Processing $\times$ Bandwidth	513.6	1.12	0.340	0.003	0
CU $\times$ Bandwidth	507.5	7.72	<0.001 ^a	0.019	0.017
Group $\times$ CU $\times$ Bandwidth	507.5	2.19	0.011 ^b	0.005	0.003
Processing $\times$ CU $\times$ Bandwidth	798.2	1.93	0.005 ^a	0.010	0.005
Group $\times$ Processing $\times$ CU $\times$ Bandwidth	798.2	1.72	0.018 ^b	0.008	0.004

^ap $\leq$ 0.01.

^bp $\leq$ 0.05.

FIG. 8. (Color online) SPL as a function of bandwidth for the nine loudness categories for participants with NH. The symbols represent mean data and the solid lines are simple linear regression fits to the data. Different symbols represent loudness category (i.e., CU of 5–45) as indicated on the right hand side. Error bars indicate ± 1 SE. Each function is an equal-loudness function of bandwidth.

that a higher stimulus level is required for narrower bandwidth signals compared to broader bandwidth signals in order to maintain equal loudness. Based on this, the greatest amount of loudness summation occurred at 20 CU for participants with NH.

Average loudness summation is plotted as a function of loudness category in Fig. 9. The error bars indicate ± 1 SE. The top panel shows data for participants with mild SNHL, and the bottom panel shows data for participants with moderate SNHL. Data are shown for unaided (circles), the SHA (squares), and the CHA (triangles). Data for participants with NH are superimposed as shaded regions in both panels for comparison. Negative slope values imply positive loudness summation. The unaided function for participants with mild SNHL has a similar pattern as the function for participants with NH up to 30 CU, but it is shifted downward, indicating less loudness summation. Above 30 CU, the function for participants with mild SNHL is above that for participants with NH, suggesting greater loudness summation. The unaided function for participants with moderate SNHL produces a pattern that differs from the one observed for participants with NH; the function is independent of loudness category.

Following amplification, the loudness summation for participants with mild SNHL (Fig. 9, top panel) has a pattern that is similar to that for participants with NH. However, the

FIG. 9. (Color online) Loudness summation for participants with mild SNHL (top panel) and moderate SNHL (bottom panel). Loudness summation was defined as the slope of the SPL vs bandwidth functions (see Fig. 8). Data are shown for unaided (circles), SHA (squares), and CHA (triangles) conditions. The error bars indicate ± 1 SE. The shaded region indicates data between ± 1 SE for participants with NH. Negative slope values imply positive loudness summation. The slope is used as a measure of the amount of loudness summation. The dotted line indicates zero loudness summation.

amount of loudness summation was greater than that for participants with NH. SHA and CHA resulted in similar loudness summation.

The loudness summation functions for participants with moderate SNHL have distinct peaks after amplification (Fig. 9, bottom panel)—at 15 CU for SHA and 25 CU for CHA. In addition, the mean amount of loudness summation is within the range of loudness summation for participants with NH for most loudness categories for SHA, and for loudness categories ≤ 25 for CHA. Unlike the case for participants with mild SNHL, the amount of loudness summation is greater than it was for participants with NH at ≥ 30 CU for CHA only. That is, the CHA resulted in the largest increase in loudness summation, but the SHA resulted in loudness summation that was more similar to the function observed for participants with NH.

Figure 10 shows deviation from normal loudness summation for participants with mild SNHL (top panel) and moderate SNHL (bottom panel). Note the difference in the plotting of the deviation from normal loudness summation (Fig. 10) compared to deviation from normal loudness (Fig. 7). This was done so that the greatest deviation would be at the bottom of the plot for both types of deviations. Deviations from normal loudness summation that are less than zero indicate that the amount of loudness summation was less than it was for participants with NH. Circles show deviations for the unaided condition, squares show results for the SHA, and triangles show results for the CHA. The error bars indicate ± 1 SE. In the unaided condition, the mean deviation from loudness summation for participants with mild SNHL (top panel) was less than zero for loudness categories ≤ 25 CU. The mean deviation exceeded zero for loudness categories ≥ 35 CU. For participants with moderate

FIG. 10. (Color online) Deviation from normal loudness summation for participants with mild SNHL (top panel) and moderate SNHL (bottom panel). The deviation from normal loudness summation was calculated for each participant with SNHL as the mean loudness summation for participants with NH minus the loudness summation for the participant with SNHL, with the data matched by loudness category (CU). Data are shown for the unaided (circles), SHA (squares), and CHA (triangles) processing conditions. The error bars represent ± 1 SE.

SNHL, the mean deviation was less than zero for loudness categories ≤ 30 CU, and exceeded zero for loudness categories ≥ 40 CU.

Both the SHA and the CHA improved loudness summation (see Fig. 10). However, loudness summation was greater than normal for participants with mild SNHL across CU for both the SHA and the CHA. For participants with moderate SNHL, loudness summation was greater than normal for loudness categories of CU > 25 when using the CHA, and at 25 and 40 CU when using SHA. In summary, amplification improved loudness summation, but resulted in greater than normal loudness summation for participants with mild SNHL. For participants with moderate SNHL, the SHA resulted in better restoration of loudness summation compared to the CHA.

The results of the repeated measures ANOVA of deviation from normal loudness summation are presented in Table II. The results revealed statistically significant main effects of Processing and CU. The main effect of Group was not statistically significant. The two-way interaction Processing $\times$ CU was statistically significant. The other two-way interactions, as well as the three-way interaction were not statistically significant.

Because the interaction Processing $\times$ CU was statistically significant, simple effects of Processing and CU were examined using least-square means at combinations of the other variable in the interaction. An analysis of the three-way interaction of Group $\times$ Processing $\times$ CU was not possible because this interaction was not statistically significant. The data are therefore collapsed across Group. The analysis shows that for the unaided condition, there were statistically significant deviations from normal loudness summation at 25 and 45 CUs. Following amplification (both SHA and CHA), there was no longer any statistically significant deviation from normal loudness summation. That is, when the data are collapsed across Group, amplification restored loudness summation for 25 and 45 CU. The complete table of least-square means and their 95% CIs are available in the supplementary material.¹

TABLE II. Analysis of variance for repeated measures of deviation from normal loudness summation for participants with SNHL. Deviation from normal loudness summation was defined for each participant with SNHL as the mean loudness summation for participants with NH (see Fig. 9) minus the loudness summation for the participant with SNHL, with the data matched by loudness category. Main effects were Group (2 levels: mild SNHL and moderate SNHL), Processing (3 levels: unaided, SHA, and CHA), CU (3 levels: 5, 25, and 45). Processing and CU are repeated measures factors within each participant. DF denotes degrees of freedom for the denominator.

Effect	DF	F value	p value	η^2	ω^2
Group	85.6	3.1	0.080	0.006	0.004
Processing	80.5	3.9	0.023 ^a	0.016	0.012
Group $\times$ Processing	80.5	1.0	0.380	0.004	-0.000
CU	83.8	4.2	0.018 ^a	0.017	0.013
Group $\times$ CU	83.8	1.7	0.180	0.007	0.003
Processing $\times$ CU	100.7	3.2	0.017 ^a	0.025	0.017
Group $\times$ Processing $\times$ CU	100.7	0.7	0.620	0.005	-0.003

^ap ≤ 0.05 .

IV. DISCUSSION

This study evaluated whether loudness growth and loudness summation can be restored using hearing-aid signal processing. This study extends previous efforts aimed at achieving this goal (Strelcyk *et al.*, 2012; Oetting *et al.*, 2016, 2017). Unlike the Oetting *et al.* (2017) study in which the gain correction to restore loudness summation was directly based on loudness measurements for narrowband and broadband signals, the current study evaluated whether suppression can be the basis for the correction factor that accounts for loudness summation. Loudness was measured using CLS. Consistent with previous studies, CLS functions for participants with SNHL in the unaided condition had a steeper slope for low-to-moderate input levels (corresponding to $CU \leq 25$) and a higher level for the softest loudness (5 CU), compared to functions for participants with NH (e.g., Brand and Hohmann, 2001; Al-Salim *et al.*, 2010; Rasetshwane *et al.*, 2015). This is indicative of threshold elevation, loudness recruitment, and a reduced dynamic range of hearing (e.g., Steinberg and Gardner, 1937; Stevens and Guirao, 1967; Scharf, 1978; Hellman and Meiselman, 1993; Rasetshwane *et al.*, 2015).

CLS functions generally (but not always) shifted to the right with decrease in signal bandwidth, indicating that a higher level was required for narrower bandwidth stimuli in order to maintain the same percept of loudness (see Fig. 5). This trend can also be observed in Fig. 8; the equal-loudness functions of bandwidth have negative slope. However, this relationship between level and bandwidth was not always monotonic, i.e., the CLS functions of Fig. 5 were not always ordered by bandwidth. The nonmonotonic pattern was especially evident in individual participant data (not shown). This suggests that although CLS can be used to measure loudness summation, the current methods are not sufficiently reliable and sensitive for application to individual data. Further refinements of the methods, such as the presentation of signals of different bandwidth within a set of trials (as opposed to measuring each bandwidth in separate sets of trials), may allow for “loudness matching,” and reduce the within-subject variability across bandwidth in CLS data.

The deviation from normal loudness analysis (Fig. 7) provides a quantification of recruitment. In the unaided condition, the mean deviation from normal loudness for participants with moderate SNHL was greater than the deviation for participants with mild SNHL for low-to-moderate input levels (corresponding to loudness categories ≤ 25 CU). Amplification with gain based on pure tones (both for the SHA and the CHA) reduced the magnitude of the mean deviation from normal loudness for low input levels for both groups, and aided CLS functions were similar to those for participants with NH (Fig. 5). However, amplification also increased the deviation from normal loudness at moderate and high levels for participants with mild SNHL and at moderate levels for participants with moderate SNHL. Overall, SHA resulted in fewer conditions with excess gain compared to CHA (see Tables S1 and S2 in the supplementary material¹), because the suppression in the SHA reduced the overall gain (see Fig. 4).

In the unaided condition, we had expected to observe less than normal loudness summation across CU, with the greatest deviations from normal loudness summation occurring for loudness categories of $CU \leq 25$, for both groups of participants with SNHL, because that is where the largest deviation from normal loudness was observed. For the most part, this was true for both groups of participants with SNHL. However, we also observed deviations from normal loudness summation for loudness categories of $CU \geq 35$ for participants with mild SNHL. One interpretation of these findings is that participants with mild SNHL had excessive loudness summation at high levels compared to participants with NH. Although greater loudness summation in individuals with SNHL has been observed following amplification (Oetting *et al.*, 2016, 2017), we have no mechanistic explanation for this observation. Both the SHA and the CHA improved loudness summation (see Fig. 10), but resulted in greater than normal loudness summation for participants with mild SNHL. For participants with moderate SNHL, the SHA resulted in better restoration of loudness summation compared to the CHA.

Several previous studies have evaluated loudness summation (e.g., Anweiler and Verhey, 2006; Bonding and Elberling, 1980; Moore and Glasberg, 2004; Oetting *et al.*, 2016). In these studies, loudness summation was expressed as the level difference between narrowband and broadband signals at equal loudness. In the current study, the slope in dB/octave of the stimulus-level versus log-bandwidth data was used as a measure of loudness summation. The advantage of using slope is that a greater amount of data can be used to quantify loudness summation as opposed to just two data points. To put the current data in perspective of previous studies, Fig. 11 compares loudness summation for participants with NH from the current study to loudness

FIG. 11. (Color online) Comparison of loudness summation for participants with NH of the current study (dashed line) to loudness summation for participants with NH of the study of Anweiler and Verhey (2006; solid line). Loudness summation is plotted as a function of the levels for the 3.2-kHz bandwidth signal ($L_{3.2\text{ kHz}}$). Negative slope values imply positive loudness summation.

summation for participants with NH from the Anweiler and Verhey (2006) study. Anweiler and Verhey measured loudness summation using CLS and noise stimuli that are similar to those used here. The data of Anweiler and Verhey (2006) are approximations obtained by digitization of their Fig. 5. To facilitate the comparison, the data of Anweiler and Verhey were converted from level difference to slope in dB/octave. The data from the current study are plotted as a function of stimulus level, instead of loudness category as was done in Fig. 9. The two loudness summation functions are similar in that they both have a local peak where the greatest amount of loudness summation occurs. However, we observed the greatest amount of loudness summation at 65 dB SPL, while Anweiler and Verhey observed it at 55 dB SPL.

The greatest amount of loudness summation for both participants with NH and with SNHL was observed at 20 or 25 CU, except for the unaided condition for participants with moderate SNHL (see Fig. 9). This is in agreement with Oetting *et al.* (2016) who observed the greatest loudness summation at 25 CU. The observation that the greatest amount of loudness summation for participants with NH was observed at moderate stimulus levels is reminiscent of the “mid-level hump” that has been observed in other measurements of loudness summation (e.g., Anweiler and Verhey, 2006; Bonding and Elberling, 1980; Moore and Glasberg, 2004; Oetting *et al.*, 2016), as well as in psychoacoustic measures of intensity discrimination (e.g., Carlyon and Moore, 1984; Nizami *et al.*, 2002; Roverud and Strickland, 2015). The mid-level hump was not evident in the loudness summation data for participants with SNHL (see Fig. 9) in the unaided condition. The mid-level hump was observed following amplification, although the aided loudness summation functions for participants with SNHL were different from the functions for NH. The fact that the mid-level hump was observed with amplification, which provides dynamic-range compression, supports the idea that the mid-level hump is a product of the mid-level compressive nonlinearity in cochlear mechanics (e.g., Pienkowski and Hagerman, 2009).

We observed negative loudness summation (positive slope in Figs. 9 and 11) at 40 and 45 CU for the participants with NH, and at 5 CU for participants with mild SNHL in the unaided condition. Although we do not have a mechanistic explanation for this observation, negative loudness summation has been observed before (e.g., Bonding and Elberling, 1980; Moore and Glasberg, 2004; Anweiler and Verhey, 2006).

The SHA signal processing restored normal loudness growth and loudness summation to some extent, but has limitations. Refinements of the SHA signal processing and the CLS-based gain-prescription strategy could lead to better restoration of normal loudness growth and loudness summation. Potential refinements to the signal processing include adjustments of the cross-channel influences due to suppression. The implementation of suppression in SHA was based on measurements of DPOAEs with a single suppressor tone and a model that assumed that suppressive effects of multiple suppressor components were additive in the intensity domain. Recent DPOAE data utilizing two suppressor tones

have indicated that the suppressive effects of multiple tones are not well described by the simple additive model that was used to mimic the effects of suppression in the design of the SHA, but are better described by a hybrid model that involves both additive-intensity and additive-attenuation models (Sieck *et al.*, 2016). Another limitation of SHA is that the cross-channel influences due to suppression were based on data from listeners with NH only. Future refinement to the signal processing should consider the hybrid model of suppression and include suppression data from listeners with SNHL. Refinements to the gain-prescription strategy should include limiting the gain prescribed at high levels.

The SHA signal processing was better at restoring loudness summation compared to the CHA because the gain for SHA accounts for the interaction of multiple frequency components of broadband sounds in a manner that mimics cochlear two-tone suppression. This suggests that suppression may be the “correction factor” that accounts for loudness summation for hearing-aid gain. With further refinement, SHA has the potential to alleviate dissatisfaction with the percept of abnormal loudness and improve satisfaction for hearing aid users.

V. CONCLUSION

The results of this study suggest that hearing-aid gain that mimics the effects of cochlear suppression may account for at least some of the interaction among multiple frequency components in the cochlea and, therefore, help to restore normal loudness growth and normal loudness summation for listeners with SNHL, especially those with moderate SNHL. However, both normal loudness and normal loudness summation were not completely restored, as the gain was excessive for high levels. Further refinements to the signal-processing and gain-prescription strategies could lead to better restoration of loudness summation across the dynamic range.

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¹See supplementary material at <https://doi.org/10.1121/1.5038274> for complete tables of least-square means and their 95% CIs for the analyses of deviation from normal loudness and deviation from normal loudness summation.

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