

Objective Binaural Loudness Balancing Based on 40-Hz Auditory Steady-State Responses. Part II: Asymmetric and Bimodal Hearing

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Abstract

In Part I, we investigated 40-Hz auditory steady-state response (ASSR) amplitudes for the use of objective loudness balancing across the ears for normal-hearing participants and found median across-ear ratios in ASSR amplitudes close to 1. In this part, we further investigated whether the ASSR can be used to estimate binaural loudness balance for listeners with asymmetric hearing, for whom binaural loudness balancing is of particular interest. We tested participants with asymmetric hearing and participants with bimodal hearing, who hear with electrical stimulation through a cochlear implant (CI) in one ear and with acoustical stimulation in the other ear. Behavioral loudness balancing was performed at different percentages of the dynamic range. Acoustical carrier frequencies were 500, 1000, or 2000 Hz, and CI channels were stimulated in apical or middle regions in the cochlea. For both groups, the ASSR amplitudes at balanced loudness levels were similar for the two ears, with median ratios between left and right ear stimulation close to 1. However, individual variability was observed. For participants with asymmetric hearing loss, the difference between the behavioral balanced levels and the ASSR-predicted balanced levels was smaller than 10 dB in 50% and 56% of cases, for 500 Hz and 2000 Hz, respectively. For bimodal listeners, these percentages were 89% and 60%. Apical CI channels yielded significantly better results (median difference near 0 dB) than middle CI channels, which had a median difference of -7.25 dB.

Keywords

asymmetric hearing, cochlear implant, bimodal hearing, binaural loudness balancing, 40-Hz auditory steady-state responses

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Introduction

Binaural hearing involves the combination, comparison, and integration in the brain of neural responses to auditory stimuli at the two ears. Benefits resulting from binaural hearing include binaural redundancy, the head shadow effect, binaural loudness summation, and binaural release from masking (e.g., Akeroyd, 2006; Avan, Giraudet, & Büki, 2015).

In case of asymmetric hearing, the brain receives distorted binaural cues. Asymmetric hearing loss is associated with worse sound source localization skills, compromised speech understanding in noise, more listening effort, poorer quality of life, and delayed development of language and cognition, although there is much variability in outcome (e.g., Köbler & Rosenhall,

2002; Lieu, 2004; Mencher & Davis, 2006; Rothpletz, Wightman, & Kistler, 2012; Vannson et al., 2015; Vila & Lieu, 2015; Wie, Pripp, & Tvete, 2010).

Asymmetric hearing is generally present for listeners with bimodal hearing, who listen through electric stimulation provided by a cochlear implant (CI) in one ear and acoustic stimulation provided by a hearing aid in the other ear. Due to relaxation of implantation criteria (Gifford, Dorman, Shallop, & Sydlowski, 2010;

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Keilmann, Bohnert, Gosepath, & Mann, 2009), an increasing number of CI users have residual hearing in the nonimplanted ear and consequently benefit from a hearing aid in the other ear (Cadieux, Firszt, & Reeder, 2013; Ching, Incerti, & Plant, 2015; Ching, van Wanrooy, & Dillon, 2007; Devocht, Janssen, Chalupper, Stokroos, & George, 2017; Dwyer, Firszt, & Reeder, 2014; Gifford et al., 2017; Tyler et al., 2002; Veugen, Chalupper, Snik, van Opstal, & Mens, 2016). However, the electrical and acoustical dynamic ranges (DRs) and loudness growth of bimodal listeners can be quite different (Blamey, Dooley, James, & Parisi, 2000). Dorman et al. (2014) found that a speech stimulus presented to the acoustical side should be approximately loudness balanced with or slightly softer than speech presented to the CI side to obtain the largest benefits for speech understanding.

Depending on the used criteria, 38% to 55% of patients have an asymmetry in their hearing (Margolis & Saly, 2008; Pittman & Stelmachowicz, 2003). Restoring binaural hearing is a rehabilitation goal. It might be accomplished by adjusting unilateral or bilateral hearing devices such that the loudness of the (amplified) sounds in the two ears resembles the loudness perceived by a normal-hearing listener (Dillon, 2012). However, the devices are usually fitted separately for bimodal listeners, and consequently, a loudness balance might not be accomplished (Francart & McDermott, 2013). Precise behavioral binaural loudness balancing might be a solution but is currently not always performed in clinical practice, because the procedures are difficult and time intensive, especially when there is a lack of fusion, that is, when a bilateral stimulus is not perceived as a single sound image. Therefore, current clinical practice usually consists of only a rough estimation of the loudness balance based on the patient's feedback, and broadband loudness balancing is probably too crude to be optimal for all patients.

The 40-Hz auditory steady-state response (ASSR) is a stable auditory evoked potential reflecting neural activity synchronized to 40-Hz amplitude modulation (Picton, 2011). Since the response can be detected fully automatically using a statistical test, it does not need any active cooperation of the participant. Van Eeckhoutte, Wouters, and Francart (2018) measured ASSR amplitudes for 38 young, normal-hearing participants for both ears, evoked using different stimulation levels and carrier frequencies. These normal-hearing participants had similar ASSR amplitude growth functions for the two ears, and the balanced loudness could be predicted with an error smaller than 5 dB in 59% of cases and smaller than 10 dB in 85% of cases. Median across-ear ratios in 40-Hz ASSR amplitudes were around 1 for normal-hearing participants. Furthermore, previous studies showed a correspondence between loudness growth

and 40-Hz ASSR growth for monaural stimulation in both acoustical hearing (Van Eeckhoutte, Wouters, & Francart, 2016) and electrical hearing (Van Eeckhoutte, Wouters, & Francart, 2017). In this study, we investigated whether the point of balanced loudness across the ears could be estimated from 40-Hz ASSR amplitudes in cases of asymmetric hearing. We tested two groups of participants: a group with asymmetric (acoustical) hearing and a group with bimodal hearing.

Material and Methods

Participants

There were nine participants with asymmetric hearing loss (three women and six men) and seven participants with bimodal hearing (four women and three men), who had at least 9.5 months of experience with their CI (median 19 months and max 36 months). In subsequent sections, we refer to these as HI and BIM participants, respectively, for asymmetric hearing-impaired and bimodal participants. The project was approved by the Medical Ethical Committee of the University Hospital of Leuven (UZ Leuven) and all participants gave their written informed consent prior to testing. Their travel expenses were reimbursed. All participants were native Dutch speakers and they were all right handed, as assessed by The Edinburgh Handedness Inventory (Oldfield, 1971).

Otoscopic examination confirmed unobstructed ear canals for all participants. Most (11) participants reported not having tinnitus, 4 participants reported a soft negligible tinnitus, and 1 participant (BIM1) reported having continuous bilateral tinnitus that did not bother the participant. This is in line with Servais, Hörmann, and Wallhäusser-Franke (2017) and Quaranta, Fernandez-Vega, D'Elia, Filippo, and Quaranta (2008), as tinnitus is generally reduced if the activity in the cochlea is restored.

The HI participants had a median age of 72 years (min 27 and max 76), and the BIM participants had a median age of 58 years (min 18 and max 87), see Tables 1 and 2. Age should not be a confounding variable, as the 40-Hz ASSR for amplitude-modulated stimuli is not affected by age for participants between 20 and 80 years (Goossens, Vercammen, Wouters, & van Wieringen, 2016; Grose, Mamo, & Hall, 2009).

Pure-tone audiometry was conducted using a Madsen Electronics Orbiter 922 audiometer and TDH-39 headset. The audiograms of the HI participants are shown in Figure 1, and the main type of hearing loss at 500 Hz and 2000 Hz is presented in Table 1, since these are the frequencies of interest for this study. Thresholds were considered to be in the normal range if they were 25 dB HL or better. Asymmetric hearing was defined as a difference

Table 1. Characteristics of the Participants With Asymmetric Hearing Loss.

ID	Sex	Age	Ear preference	500 Hz		2000 Hz	
				Right	Left	Right	Left
HI1	M	52	Right	NH	SNHL	NH	SNHL
HI2	M	75	Left	Mixed	Conductive	SNHL	SNHL
HI3	M	75	Left	Mixed	NH	Mixed	SNHL
HI4	M	54	Right	NH	Mixed	NH	SNHL
HI5	F	37	Left	Conductive ^a	Conductive ^a	Conductive	Conductive
HI6	M	26	Right	NH	Conductive	NH	Mixed/SNHL ^b
HI7	F	75	Right	NH	Conductive	NH	Mixed
HI8	M	72	Left	SNHL	NH	SNHL	NH
HI9	F	75	Left	SNHL	SNHL	SNHL	SNHL

Note. The participant ID number, sex, age (in years), ear preference, and for each ear the hearing loss type for the 500 Hz and 2000 Hz test frequencies. NH = normal threshold; SNHL = sensorineural hearing loss; M = male; F = female; mixed = elevated air and bone conduction thresholds with air-bone gap; conductive = air-bone gap with normal bone-conduction threshold; HI = asymmetric hearing-impaired participant.

^aThis participant had normal air-conduction thresholds of 15 and 20 dB for the right and left ears, respectively, but also air-bone gaps of 25 dB for both ears at this test frequency.

^bThe bone-conduction threshold of this participant could not be assessed due to overmasking.

Table 2. Characteristics of the Participants With Bimodal Hearing.

ID	Sex	Age	Ear preference	Implant type	CI test channel	Acoustic test frequency
BIM1	F	76	Left (CI)	CI522	20/17	500 and 1000 Hz
BIM2	F	87	Left (ac)	CI512	11/8	2000 Hz
BIM3	F	25	Right (CI)	CI422	20/17	500 Hz
BIM4	M	18	Left (ac)	CI422	11/8	2000 Hz
BIM5	M	71	Right (ac)	CI522	11/8	2000 Hz
BIM6	F	57	Left (ac ^a)	CI522	22/19 ^a	500 Hz
BIM7	M	58	Right (ac)	CI522	20/17	500 Hz

Note. The participant ID number, sex, age (in years), the ear preference (CI side or ac: acoustic side), the implant type, CI test channel (bipolar stimulation), and acoustic test frequency. M = male; F = female; CI = cochlear implant; BIM = bimodal participant.

^aThis participant had a hybrid implant and consequently had a different frequency map than the other participants.

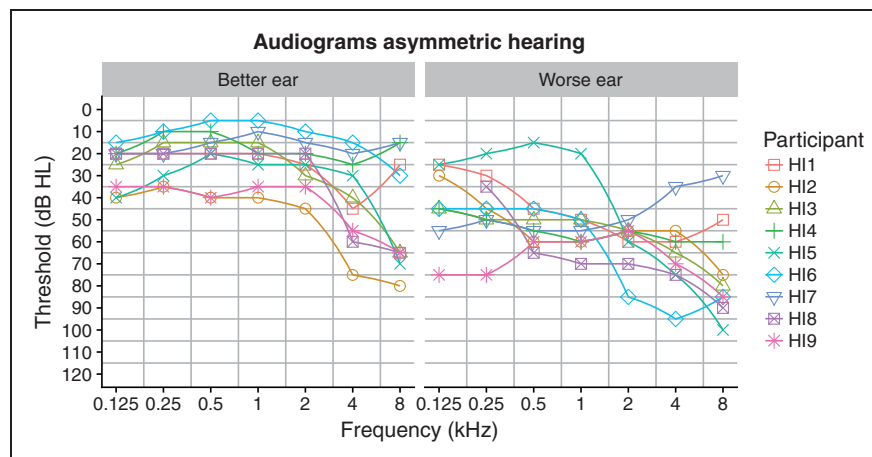


Figure 1. The behavioral detection thresholds (air conduction) of the better and worse ears of the participants with asymmetric hearing. HI = asymmetric hearing-impaired participant.

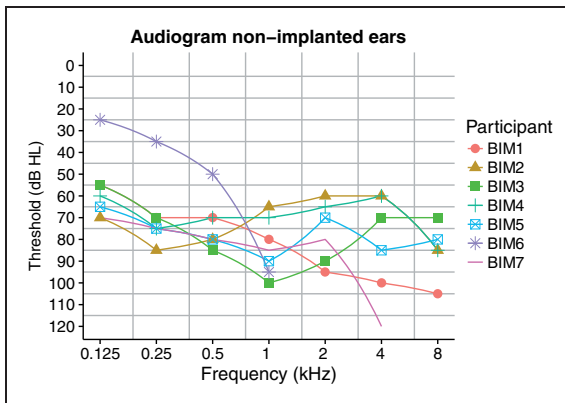


Figure 2. The behavioral detection thresholds (air conduction) for the nonimplanted ear of the participants with bimodal hearing. BIM = bimodal participant.

in air conduction thresholds of at least 20 dB at one or both test frequencies (500 or 2000 Hz). Details of the hearing of the BIM participants are presented in Table 2 and the audiograms of the nonimplanted ears are shown in Figure 2.

Responses to Questions 13 to 16 of the questionnaire of Coren (1993) were used to calculate ear preferences. As expected, all HI participants had a preference for the better ear, and this was not related to handedness. Two BIM participants (BIM1 and BIM3) had a preference for the electrical side, and the remainder had a preference for the acoustical side.

Stimuli and Apparatus

Behavioral testing was performed in a soundproof booth for the HI participants with asymmetric hearing loss and in a normal, quiet room for the BIM participants. Electroencephalographic (EEG) measurements took place in an electromagnetically shielded soundproof booth.

The acoustic stimuli were 100% sinusoidally amplitude-modulated sinusoids with a modulation frequency of 40 Hz and a carrier frequency of 500, 1000, or 2000 Hz. They were created in MATLAB R2013a (The MathWorks, Inc., Natick, MA). All HI participants were tested using the 500- and 2000-Hz carrier frequencies. For the BIM participants, the carrier frequency that yielded the lowest audiometric threshold in the nonimplanted ear was chosen as the test frequency in order to have a broad enough DR. The acoustic stimuli were presented through Etymotic Research ER-3 A insert ear phones, connected to an RME Hammerfall DSP Multiface II sound card. Each insert phone was calibrated using a 2CC Brüel & Kjær coupler, type 4152.

For the BIM participants, the electric stimuli were 40-Hz sinusoidally amplitude-modulated biphasic cathodic-first pulse trains presented to the implanted ear

though a research processor (L34) and programming device, controlled by the Nucleus Implant Communicator interface, all provided by Cochlear Ltd. The pulse trains had a pulse rate of 900 pps, an inter-phase gap of 8 μ s, and a pulse width of 60 μ s, and they were presented in bipolar mode (BP + 2). This combination of parameters allowed the use of linear interpolation over the duration of the CI artifact as a method for CI artifact removal in the EEG (Deprez et al., 2017; Hofmann & Wouters, 2012). The CI channel whose pass-band included the test carrier frequency in the participants' everyday clinical map was chosen as the test channel. One participant (BIM1) was tested at both 500 and 1000 Hz. The CI stimuli were verified with an oscilloscope and a CI mounted in a box, with exposed electrode leads (implant-in-a-box).

All stimuli were presented over a range of sound pressure or current levels encompassing the participants' DRs. The stimulus duration for both electric and acoustic stimulation was 1 s for behavioral tests, since temporal integration is certainly complete after 1 s (Marks & Florentine, 2011). The stimulus duration was 307.2 s for EEG recordings (300 epochs) to reduce the EEG recording noise. As 40-Hz ASSR amplitudes are not affected by loudness adaptation (Van Eeckhoutte, Luke, Wouters, & Francart, 2018), the stimulus duration probably did not affect the results.

The software program APEX3 was used for behavioral testing (Francart, van Wieringen, & Wouters, 2008). For EEG recordings and for the determination of the electric DR, the stimuli were presented using the software platform for the recording and analysis of brain responses to auditory stimulation (Hofmann & Wouters, 2012), with a signal sampling rate of 96 kHz. The EEG was recorded using ActiveTwo System Software (Biosemi) with a recording sampling rate of 8192 Hz and a head cap of 64 + 2 Ag/AgCl active scalp electrodes that followed the standard 10 to 20 electrode position system.

Procedures and Data Analysis

Determination of DR. The behavioral DR was assessed for each stimulus and each ear separately. The detection threshold (the so-called T level in case of CI stimulation) was defined as the lowest level at which the participant perceived a sound. The maximum acceptable level was defined as the level perceived as loud to very loud.

For the HI participants, the detection threshold was determined using an adaptive, one-up, two-down, three-alternative forced-choice procedure without feedback (Jesteadt, 1980; Levitt, 1971). Each interval was indicated on the screen, with a 1 s interstimulus interval. The participant had to indicate which interval out of the three contained the stimulus. Based on the responses, the level of the stimulus changed with step sizes of 10, 5,

and 2 dB after 0, 1, and 3 reversals, respectively. After six reversals, the task ended. The detection threshold was calculated as the mean level over the last six trials.

The maximum acceptable level was found using an adjustment procedure. The participant had to indicate the loudness of each stimulus on a Graphical Rating Scale with loudness categories “Inaudible,” “Very Soft,” “Soft,” “OK or Comfortable,” “Loud,” “Very Loud,” and “Unbearable” (Van Eeckhoutte et al., 2016). For each trial, the participant could choose any position on the scale, including between the loudness categories. The first level was slightly above the detection threshold and the experimenter increased the level, depending on the feedback of the participant, to the maximum acceptable level.

For the BIM participants, an adjustment procedure was used to find both the detection threshold and maximum acceptable level for both the electrical and acoustical stimulus. For the electrical stimulus, unmodulated pulse trains were first presented in bipolar mode to find the unmodulated T level (T_{unmod}). The start level was set at a level below the T level of the participant’s clinical map in monopolar mode, to start at a safe level that was inaudible for the participant. Second, the levels were increased to find the maximum acceptable level of the unmodulated pulse train (Max_{unmod}). Third, the maximum acceptable level was found for an amplitude-modulated pulse train, modulating between the unmodulated T level and a changing maximum level (Max_{mod}). The modulation depth was chosen as the difference between this modulated maximum acceptable level and the unmodulated T level. This amplitude modulation depth was fixed to find the modulated T level (T_{mod}). The final DR to be used was determined as the difference between the modulated maximum acceptable level and the modulated T level, also found using the adjustment procedure. The maximum possible level was 255 current units. For the acoustical stimulus for the BIM participants, an adjustment procedure was also used to find the threshold and maximum acceptable level, the latter using the same procedure as for the HI participants.

Behavioral loudness balancing. Binaural loudness balancing was performed for each stimulus using an adjustment procedure. For the HI participants, binaural loudness balancing was performed with a fixed level in the better ear, that is, the reference ear. The procedure was similar to the one used for normal-hearing participants. This fixed level corresponded to either 40% or 70% of the stimulus DR in dB for that ear. The level at the other ear was variable and started at 8 dB above the measured detection threshold of the stimulus. The stimuli were presented simultaneously to the two ears, which presumably resulted in a lateralization task for most participants. They were instructed to make the sounds of the left

and right ear equally loud, and that it may help to search for a balanced percept in the middle of their head if the sounds are fused to one auditory image. The participant had to adjust the level of the variable ear in steps of 1 dB until the loudness was perceived as balanced in loudness across both ears. The participant was asked to find the balanced loudness at least twice, from opposite lateralization sides (i.e., two tracks: from soft to equally loud and then to louder and from louder to equally loud and then to softer). The average of the two balanced levels was used as the final loudness balance estimate. The different levels and carrier frequencies (i.e., conditions) were randomized across participants. More details about this procedure can be found in Van Eeckhoutte, Spirrov, and Francart (2018).

An auditory stimulus is fused if a bilateral stimulus is perceived as a single sound image. Bimodal listeners can experience large binaural pitch fusion ranges, if they fuse stimuli that individually evoke different pitches in the two ears. Binaural pitch fusion ranges are abnormally wide for bimodal listeners, with dichotic fusion frequency ranges of 1 to 4 octaves (Reiss, Ito, Eggleston, & Wozny, 2014). Therefore, the BIM participants in this study were first involved in a short, rough procedure matching the pitch of the acoustical stimulus to that of the CI stimulus in the other ear before conducting the binaural loudness balancing task. We wanted to avoid large pitch mismatches across ears because those could negatively influence the just noticeable difference in interaural level (Francart & Wouters, 2007). For this procedure, the stimuli were set at a comfortable loudness. The participant first heard the CI stimulus for 1 s followed by one of the three modulated acoustical stimuli with carrier frequencies of 500, 1000, and 2000 Hz, which also had a duration of 1 s, in random order. The participant was asked to indicate which acoustical stimulus had a pitch that was best matched with the CI stimulus, ignoring small loudness differences. All participants reported that the selected acoustical stimulus was roughly pitch matched to the CI stimulus.

The behavioral loudness balancing procedure for the BIM participants was similar to that for the HI participants. The CI ear was chosen as the reference ear with fixed current level. Loudness balancing was performed at different reference levels encompassing the DR. As many reference levels as possible were tested, depending on the time available. In most cases, levels of 35%, 55%, and 75% of the DR were tested, but 15%, 45%, 65%, and 85% were also sometimes used. As bimodal listeners usually do not perceive a fused auditory image when listening to simultaneous presentation of the stimuli, the stimuli were presented sequentially. The participants first heard the 1-s electrical stimulus, then 1-s of silence, and then the 1-s acoustical stimulus in the other ear. Time also allowed

behavioral loudness balancing using simultaneous presentation of the electrical and acoustical stimuli, for a few participants who could perform this task.

EEG measurements. After the behavioral tests, the participants sat in a comfortable chair and watched a silent but subtitled movie of their own choice during EEG recordings. This ensured that the participants did not fall asleep and it was intended to control for large fluctuations in attention across participants and measurement conditions. Breaks were given when desired, with at least one break halfway through testing. Even though not necessary, as no adaptation effects are found for the ASSR (Van Eeckhoutte, Luke, et al., 2018), for the HI participants the left and the right ears were stimulated in alternation, and the different carrier frequencies were presented consecutively (thus, first all conditions of one carrier with alternating left and right ear stimulation, then all conditions of the other carrier frequency). For the BIM participants, the EEG was recorded first to electrical stimulation and then to acoustical stimulation to allow connection of the EEG electrodes that were on top of the CI coil during acoustical stimulation.

For the HI participants, the EEG was recorded to stimuli with levels corresponding to 25, 40, 55, 70, and 85% of the DR in dB, presented monaurally (thus 5 Levels \times 2 Carrier Frequencies \times 2 Ears, giving 20 conditions). For the BIM participants, the levels were 35%, 45%, 55%, 65%, 75%, and 85% of the DR in current level (electrical stimulation) or in dB (acoustical stimulation). Slightly more conditions were tested because we had more time available (6 Levels \times 2 Types of Stimulation, giving 12 conditions). The time between two recordings was at least 10 s.

The data were analyzed using MATLAB R2013a (The MathWorks, Inc., Natick, MA). All raw data were converted into epochs of 1.024 s each. For electrical stimulation, the EEG is contaminated with CI stimulation artifacts. Linear interpolation was used from 100 μ s before the onset of a stimulation pulse to 1,000 μ s after the offset of the stimulation pulse to remove these artifacts. Thus, for each interpulse interval (of 1.1 ms in case of a pulse rate of 900 pps), at least one sample per pulse period is retained (Hofmann & Wouters, 2012). Thus, the linear interpolation method (also known as blanking) during the duration of the CI artifact cuts out the artifact and interpolates between the other remaining samples. Furthermore, 5% of the epochs with the highest peak-to-peak amplitude were rejected to remove any other artifacts. A second-order butterworth high-pass filter with a cutoff frequency of 2 Hz was applied. The data were referenced to recording electrode Cz, with the exception of participant BIM4, for whom Fz was used because Cz was a noisy recording electrode. A Hotelling t^2 test was applied to the amplitude and phase of the

FFT-bin closest to the modulation frequency across epochs to determine the absence or presence of the response. The noise floor was estimated based on the standard deviation across trials. The significance level was set at $\alpha = .05$. Only significant responses were taken into account. The electrode selections for investigating responses of the left and right hemispheres, respectively, were “P1, P3, P5, P7, P9, PO3, PO7, O1” and “P2, P4, P6, P8, P10, PO4, PO8, O2.” The amplitudes for the electrode selection “Both hemispheres” were the average of the amplitudes of the electrodes for the two hemispheres and the midline electrodes Iz, Oz, POz, and Pz. For electrical stimulation, only the electrodes contralateral to the CI stimulation side were considered, to reduce remaining CI stimulation artifacts. In addition, if the noise amplitude exceeded 0.06 μ V on a particular EEG recording electrode, the response amplitude at that electrode was not taken into account; 0.06 μ V was the highest noise floor across all participants.

Data analysis. The ASSR amplitudes as a function of stimulation level were smoothed with a second-order polynomial, and this fitted function was used in all further analyses, which were performed using R version 3.3.1 (2016, R Core Team).

An example of the data analysis is shown in Figure 3 for the 2000-Hz 70% DR condition for participant HI1. First, the ratio was calculated of the ASSR amplitudes corresponding to the levels that were judged as balanced in loudness (see Figure 3(a)). For the participant and condition in the example, the ASSR amplitude corresponding to the reference level of 73 dB SPL in the right, fixed ear was 0.2295 μ V. The ASSR amplitude corresponding to the level in the left ear that was behaviorally balanced with the reference level, 78 dB SPL, was 0.2030 μ V, yielding a ratio of 1.13.

Second, the balanced level was predicted based on the ASSR amplitude for the level at the fixed ear. For the variable ear, the level giving the same ASSR amplitude as for the fixed ear was found. The balanced level predicted from the ASSR amplitudes was subtracted from the behaviorally balanced level, as shown in Figure 3(b). The same ASSR amplitude as for the reference level occurred at 80.3 dB SPL in the left ear. As the behaviorally loudness balanced level was 78 dB SPL, the difference between the behaviorally balanced level and the ASSR-predicted balanced level was -2.3 dB, for this participant and condition.

For the HI participants, the calculations were done for the ASSR amplitudes of the three electrode selections (“Left hemisphere,” “Right hemisphere,” or “Both hemispheres”). For the BIM participants, this was done for the ASSR amplitudes of the electrode selection corresponding to the hemisphere contralateral to the CI side.

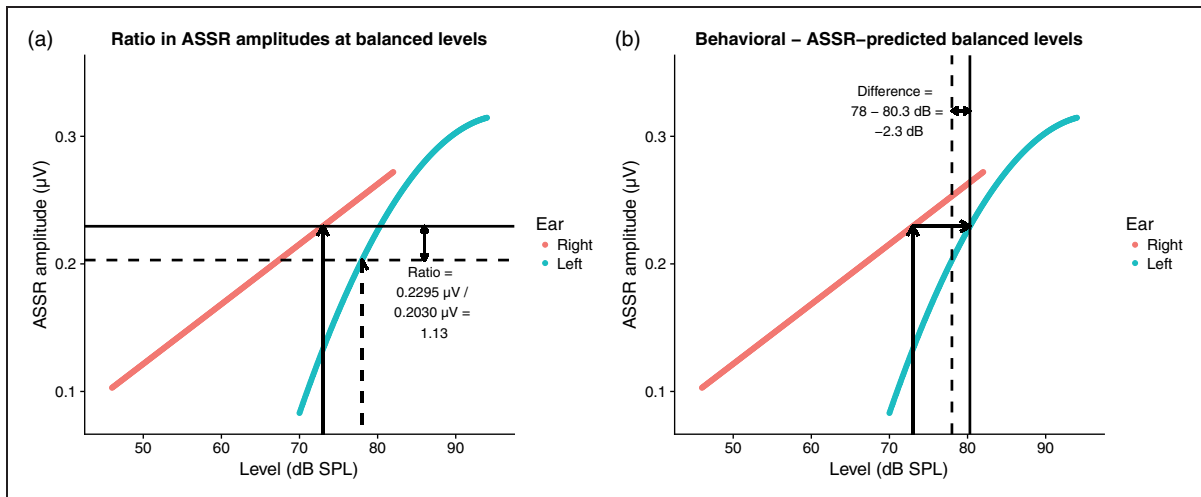


Figure 3. Example of the analyses. For this participant (HI1) and condition (2000-Hz carrier frequency), the reference, fixed level was 73 dB SPL in the right ear. The balanced level measured behaviorally was 78 dB SPL and is indicated by the dashed vertical lines. (a) An example of the ratio of the ASSR amplitudes at the reference level and the balanced level found behaviorally. (b) An example of the difference in dB between the behaviorally balanced levels and the ASSR-predicted balanced levels. The vertical continuous line indicates the ASSR amplitude observed when the right ear was stimulated at the reference level of 73 dB SPL. ASSR = auditory steady-state response.

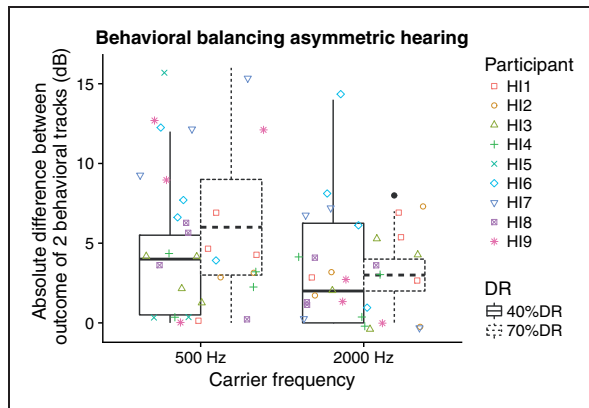


Figure 4. The difference between the levels judged as balanced in loudness found using the two tracks (of opposite lateralization sides) of the behavioral loudness balancing adjustment procedure for all HI participants. DR = dynamic range; HI = asymmetric hearing-impaired participant.

Wilcoxon rank-sum tests were used to assess whether the ratios or the differences in dB were significantly different from 1 or 0, respectively, with the significance level set at $\alpha = .05$.

Results

Acoustical Asymmetric Hearing

Behavioral loudness balancing. The absolute differences between the balanced levels found with the two tracks of the behavioral balancing adjustment procedure for all

participants are shown in Figure 4. In 60% of cases, the differences between the balanced levels of the tracks were less than 5 dB. However, the difference ranged up to 16 dB, indicating that some participants found it hard to perform behavioral loudness balancing.

ASSR amplitude growth functions. The ASSR amplitude growth functions for the right and left ears of the HI participants are shown in Figures 5 and 6. The amplitudes in the figures were obtained with the electrode selection “Both hemispheres,” but similar results were obtained with the electrodes selections “Right hemisphere” and “Left hemisphere.”

In cases where one ear had normal hearing and the other ear had a sensorineural hearing loss for that carrier frequency, the amplitudes for the better ear grew more slowly than the amplitudes for the worse ear. Thus, the amplitude growth functions approached each other at high levels (HI1 and HI8 at 500 Hz, and HI1, HI4, and HI8 at 2000 Hz). In cases with purely a conductive hearing loss, more parallel ASSR amplitude growth functions were found, such as for HI5 at 2000 Hz.

Across-ear ratios in ASSR amplitude. Figure 7 shows the ratios between ASSR amplitudes of the right and left ears at behaviorally balanced levels. The median ratios were close to 1, for all balanced levels, carrier frequencies, and electrode selections. For the 500-Hz carrier frequency and 70% of the DR condition, variability was higher than for the other conditions. The three outliers in Figure 7 are from the same participant. Across all combinations of carrier frequencies, percentage of the DR,

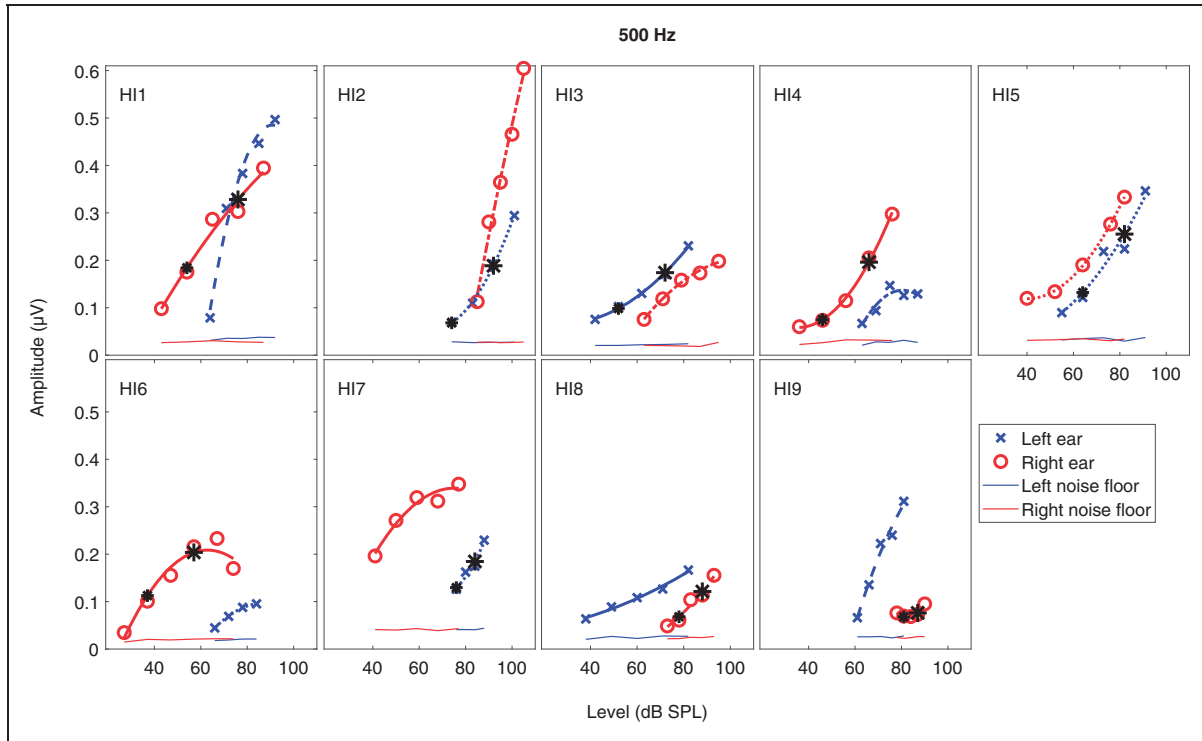


Figure 5. ASSR amplitude growth functions measured for right (red) and left (blue) ear stimulation of the HI participants, for the 500-Hz carrier frequency. The data were fitted using a second-order polynomial. The results obtained using the electrode selection “Both hemispheres” are shown. The line types indicate the types of hearing loss at that carrier frequency: a continuous line for normal hearing, a dashed line for sensorineural hearing loss, a dotted line for a conductive hearing loss, and a dash-dotted line for mixed hearing loss. The thin continuous line indicates the measured EEG noise floor. The smaller and larger asterisks indicate the ASSR amplitudes at 40% and 70%, respectively, of the dynamic range of the reference ear. HI = asymmetric hearing-impaired participant.

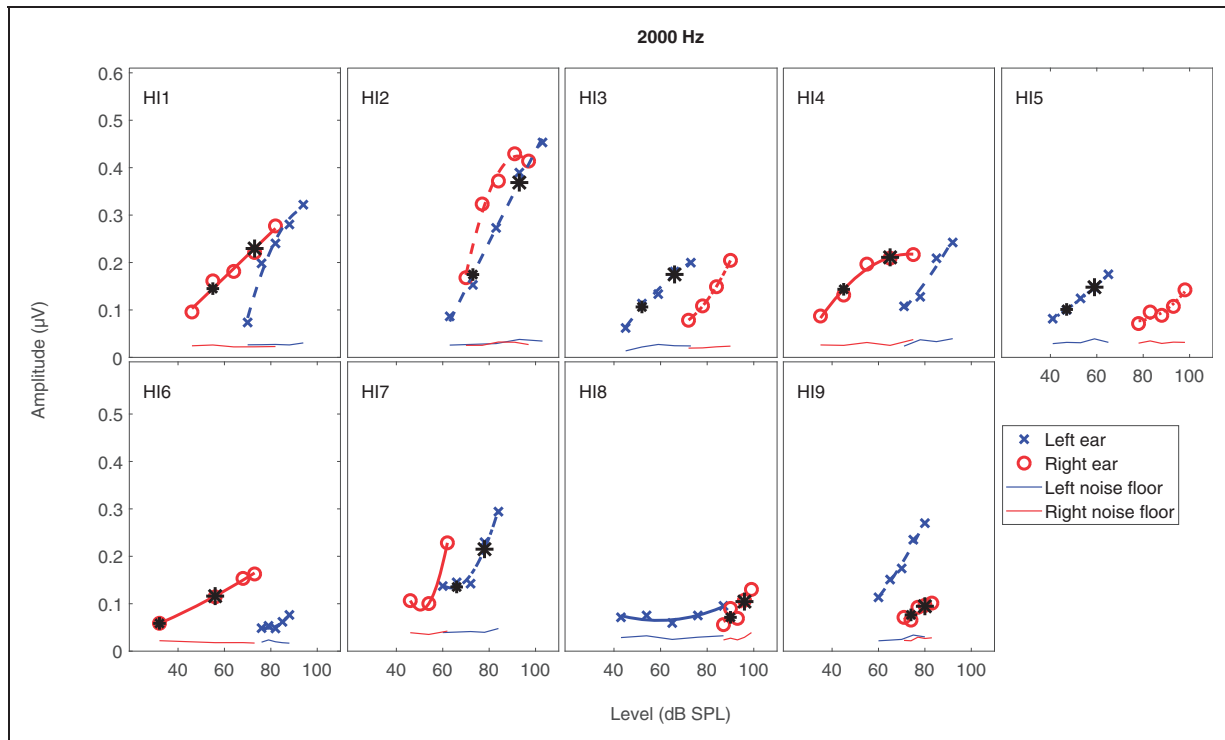


Figure 6. As Figure 5 but for the 2000-Hz carrier frequency. HI = asymmetric hearing-impaired participant.

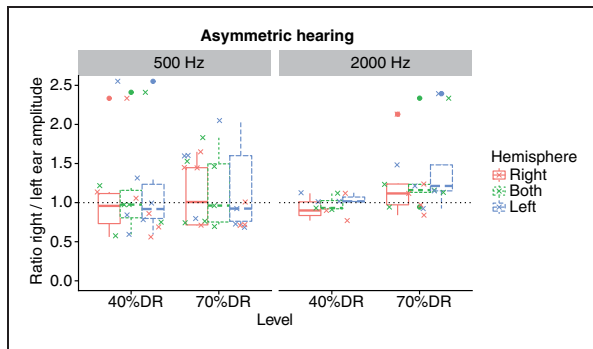


Figure 7. The ratios in ASSR amplitude between the right and left ears for the HI participants, for the stimulation levels that were behaviorally loudness balanced as measured at 40% and 70% of the dynamic range of the reference ear. The filled dots are the outliers of the boxplots. DR = dynamic range.

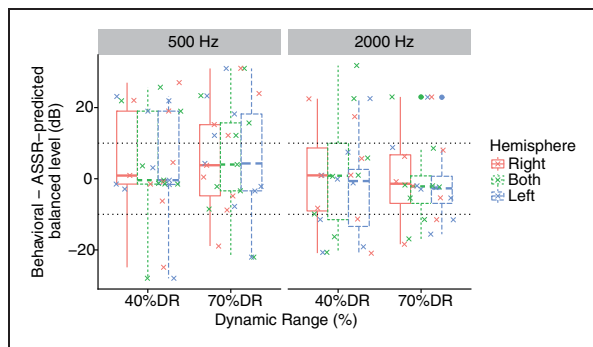


Figure 8. The difference between the behavioral loudness balance levels and the ASSR-predicted balance levels for the participants with asymmetric hearing loss. The dotted lines represent ± 10 dB and the filled dots are the outliers of the boxplots. DR = dynamic range; ASSR = auditory steady-state response.

and electrode selection, the median ratios were between 0.90 and 1.21. Wilcoxon rank-sum tests for each combination showed that median ratios were not significantly different from 1 (all p values $> .05$, after Holm correction).

Predicted balance point. Figure 8 shows the differences between the behaviorally found balance levels and the ASSR-predicted balance levels. Slightly more variability for the 500-Hz carrier frequency was found than for the 2000-Hz carrier frequency (this was also the case for the behavioral loudness balancing results). Median differences ranged from -2.7 to 3.8 dB across combinations of carrier frequencies, percentages of the DR, and electrode selections. In total, 37% of the data points were in the 5 dB error range and 53% in the 10 dB error range. For the 500-Hz carrier frequency, the percentages were 43% and 50% for the 5 and 10 dB error ranges,

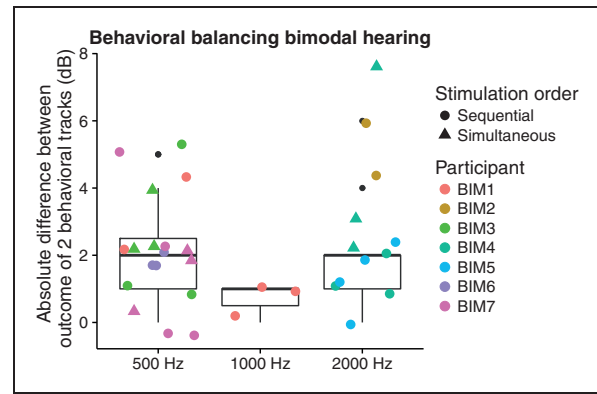


Figure 9. The difference between the levels judged as balanced in loudness found using the two tracks of the behavioral loudness balancing adjustment procedure for all participants with bimodal hearing (sequential presentation, also indicated with jittered dots). Participants BIM3, BIM4, and BIM7 were also tested using simultaneous presentation of the stimuli (indicated with triangles, not included in the boxplots). The carrier frequency was chosen based on the audiogram of the participants, with BIM1 the only participant tested at 1000 Hz. BIM = bimodal participant.

respectively, and for the 2000-Hz carrier frequency, they were 48% and 56% for the 5 and 10 dB error ranges. Wilcoxon rank-sum tests for each combination showed that median differences were not significantly different from 0 dB (all p values $> .05$).

Bimodal Hearing

Behavioral loudness balancing. Moderate variability was observed for the behavioral balancing results of the BIM participants (see Figure 9). The absolute differences between the acoustical levels for the two tracks of the adjustment procedure had median values of 2, 1, and 2 dB, and most values were smaller than 5 dB. However, some participants found it difficult to perform behavioral loudness balancing, such as BIM2. For the three participants who were involved in behavioral loudness balancing using simultaneous presentation of the stimuli, no clear difference between the two modes of presentation was observed. A Wilcoxon signed-rank test indicated that the results for the two procedures were not significantly different from each other ($V = 10$, p value = .548).

ASSR amplitude growth functions. The ASSR amplitude growth functions for the acoustical and electrical sides are shown in Figure 10. For most of the participants, the ASSR amplitude growth functions for the acoustical and electrical stimulation sides were similar. However, the ASSR amplitudes for CI stimulation channels 11/8 were slightly larger than for the corresponding acoustical carrier frequency 2000 Hz, such as for BIM2, BIM4, and

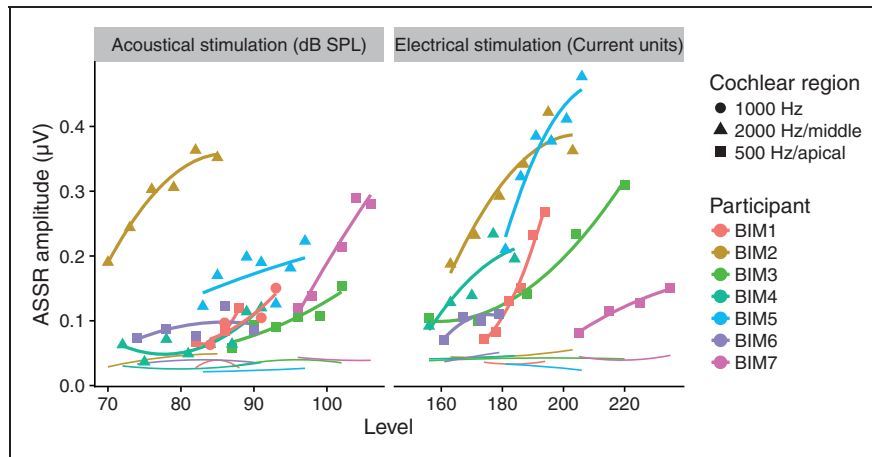


Figure 10. The ASSR amplitudes for each bimodal participant, for the acoustical and electrical sides, with a different color for each participant. The circles, triangles, and crosses indicate the different acoustical carrier frequencies and their corresponding CI stimulation channels. Each thin line indicates the participant's noise floor. BIM1 was tested using carrier frequencies of 500 Hz and 1000 Hz and for one apical CI channel. ASSR = auditory steady-state response; BIM = bimodal participant.

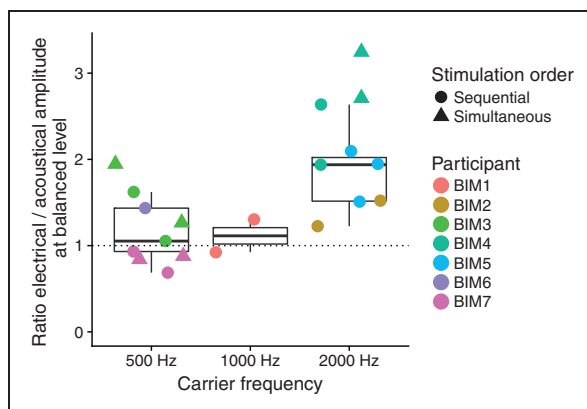


Figure 11. The ratios between the electrical ASSR amplitude and the acoustical ASSR amplitude corresponding to the balanced levels, as measured behaviorally. The boxplots and the dots represent sequential presentation and the triangles simultaneous presentation. BIM = bimodal participant.

BIM5. This difference was not clearly observed for the ASSR amplitudes of the 500- and 1000-Hz carrier frequencies and the corresponding CI stimulation channels.

Across-ear ratios in ASSR amplitudes. Figure 11 shows the ratios between the ASSR amplitudes of the electrical and acoustical sides at the behaviorally balanced levels. The median ratios were 1.05 and 1.11 at 500 and 1000 Hz, respectively. However, the median ratio was much larger for the 2000-Hz carrier frequency (1.94).

For the 500-Hz carrier, the ratios were not significantly different from 1 ($V = 15$, $p = .063$, 95% CI [0.69, 1.62]), while for the 2000-Hz carrier, the ratios were significantly different from 1 ($V = 28$, $p = .016$, 95% CI

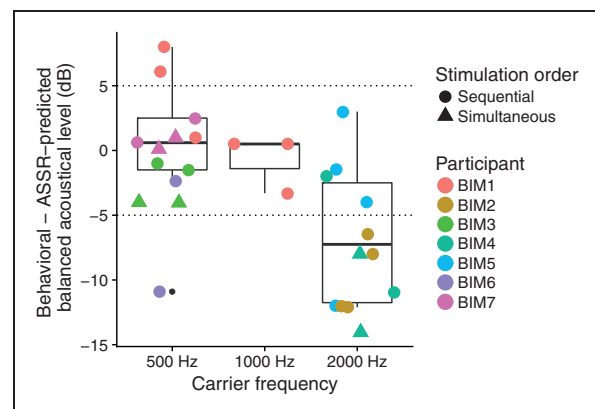


Figure 12. The differences in dB between the behaviorally balanced acoustical level and the ASSR-predicted acoustical level. The current levels of the electrical side were always fixed, and the levels of the acoustical side were varied. The boxplots and the dots represent sequential presentation, and the triangles simultaneous presentation. ASSR = auditory steady-state response; BIM = bimodal participant.

[1.37, 2.29]). We did not perform a statistical test for the 1000-Hz carrier frequency, as there were too few data points.

Predicted balance point. The differences between the acoustical levels that were behaviorally balanced with the electrical side and the ASSR-predicted balance levels are shown in Figure 12. The median differences were 0.6 and 0.5 dB at 500 and 1000 Hz, respectively, while the median difference was -7.25 dB at 2000 Hz. For sequential stimulation and the 500-Hz carrier frequency, 67% and 89% of the differences were smaller than 5 and

10 dB, while these percentages were 40% and 60% for the 2000-Hz carrier frequency.

Wilcoxon rank-sum tests indicated that the median difference was not significantly different from 0 dB for the 500-Hz carrier frequency ($V = 20.5$, $p = .859$, 95% CI [-4.30, 4.95]), while it was significantly different from 0 dB for the 2000-Hz carrier frequency ($V = 52$, $p = .014$, 95% CI [2.00, 11.50]).

Discussion

Acoustical Asymmetric Hearing

In the HI group, the ASSR amplitude growth often resembled the behavioral loudness growth. In cases of conductive hearing loss in both ears, parallel ASSR amplitude growth functions were observed, with the worse ear just needing a higher level to obtain the same ASSR amplitude or loudness. In cases of purely sensorineural hearing loss in both ears, the worse ear had steeper ASSR amplitude growth functions, which is similar to behaviorally described loudness recruitment (Moore, 2012). This resembles “physiological recruitment” (Dimitrijevic et al., 2002; Picton, Dimitrijevic, Perez-Abalo, & Van Roon, 2005), which can be related to loudness recruitment. However, while median ratios were close to 1 (0.90 and 1.21) at balanced levels, deviations were observed.

For a few participants (e.g., HI9), the ASSR amplitudes remained very small with increasing stimulus level and remained close to the noise floor. The small amplitudes are likely due to neural loss. Based on the questionnaires, all participants with asymmetric hearing loss reported a preference for the better ear, irrespective of their handedness. Perhaps a smaller ASSR amplitude for the worse ear indicates that the participant neglected that ear (Hood, 1984) or that there was less neural survival.

The median differences between ASSR-predicted balance levels and behaviorally found balance levels were close to 0 dB (with median values between -2.7 and 3.8 dB), but variability across participants was observed, especially for the 500-Hz carrier frequency. Only 50% and 56% of the data points had an error of 10 dB or smaller, for the 500 and 2000-Hz carrier frequencies. The greater errors at 500 Hz could be explained by the fact that there was more variability in behavioral loudness balancing at 500 Hz.

The results were similar for all EEG electrode selections, so there was no evidence for hemispheric differences.

Bimodal Hearing

For the BIM participants, a median ratio of 1.05 between ASSR amplitudes at balanced levels was found for the apical CI channel and 500 Hz (and a

ratio of 1.11 for 1000 Hz, but this was only tested in one participant). For the CI channel 11/8 and 2000-Hz stimulation, the CI side had larger ASSR amplitudes, yielding a median ratio between ASSR amplitudes at balanced loudness of 1.94. Similarly, the median differences between the ASSR-predicted balance levels and the behavioral balance levels were close to 0 dB (0.6 dB) for apical CI channels and the 500-Hz carrier frequency, while at 2000 Hz, the ASSR amplitudes overestimated the behavioral balance levels (with a median value of 7.25 dB).

The difference in results between carrier frequencies cannot be the result of better low-frequency residual hearing, which is commonly found for participants with bimodal hearing. We always chose the carrier frequency with the best threshold in the audiogram and thus the largest DR for testing. A possible explanation is related to the effect of CI channel and the corresponding place of stimulation in the cochlea. Although Van Eeckhoutte et al. (2017) found a good correspondence between electrically evoked ASSR amplitude and loudness growth for apical and mid CI channels, better correspondence to loudness growth (smaller mean square errors) was obtained for CI Channel 15 than for CI Channel 6 for monaural stimulation. In the study measuring monaural loudness growth functions with acoustical stimulation (Van Eeckhoutte et al., 2016), we also found slightly better results (smaller mean-square errors) for the 500-Hz than for the 2000-Hz carrier frequency, which stimulate different locations in the cochlea. However, in this study, the difference between the right- and the left-ear amplitudes at balanced levels for the HI participants was similar at 500 and 2000 Hz, with smaller standard deviations at 2000 Hz.

We could not investigate hemispheric differences for the BIM participants, as we used the electrode selection contralateral to the CI ear to reduce CI stimulation artifacts. Furthermore, we used bipolar stimulation for the BIM participants, as the resulting CI stimulation artifacts can then be efficiently removed using linear interpolation (Hofmann & Wouters, 2012). As there might be additional effects of spread of excitation, it is unclear to what extent the results will be similar when using monopolar stimulation, which is used in commercial CIs. More advanced CI artifact techniques are currently being developed for this mode of stimulation (Deprez et al., 2017). However, we do not expect large differences between modes of stimulation.

Neural Correlates of Binaural Loudness

Previous researchers have suggested the use of electrophysiological measures for matching loudness for the two ears, since loudness growth might differ across the ears, and interaural level differences (ILDs) are the most

important binaural cues for bimodal listeners (Francart & McDermott, 2013).

Salloum et al. (2010) and Gordon, Abbasalipour, and Papsin (2016) suggested the use of electrically evoked auditory brainstem response (EABR) amplitudes to find bilaterally balanced levels for children with bilateral CIs. In line with our results for 40-Hz ASSR amplitudes, they found that current levels that evoke the same EABR wave V amplitude were judged as balanced across the ears by 69% of children, and that lateralization occurred toward the side with the larger amplitude response. However, Kirby, Brown, Abbas, Etler, and O'Brien (2012) did not find evidence of equal loudness percepts at equal amplitudes for the two ears in bilateral CI users, for EABRs and electrically evoked compound action potentials, as the differences in perceived loudness across ears for stimuli matched for response amplitudes were 13% to 50%. Loudness growth for each ear was measured by using a loudness scale from 1 to 100.

The binaural interaction component (BIC) has also been used to investigate binaural processing. The BIC is the result of subtracting the response amplitudes evoked by the binaural stimulus from the summed amplitudes evoked by the monaural stimulus. Smith and Delgutte (2007) reported that the EABR-BIC amplitude was maximal in implanted cats when the stimuli had an ILD that corresponded to levels at each ear that produced similar monaural EABR amplitudes. However, Van Yper, Vermeire, De Vel, Battmer, and D'Hooge (2015) questioned the clinical use of the (E)ABR-BIC amplitudes for individual diagnosis, as the response was absent in a proportion of normal-hearing participants, and low signal-to-noise ratios make interpretation of the responses challenging.

In a similar way, the ASSR-BIC amplitudes can be calculated after deriving the response amplitudes from the response spectrum. Zhang and Boettcher (2008) found the largest 80-Hz ASSR-BIC amplitudes at an ILD of 0 dB for normal-hearing listeners. Similarly, Massoud, Aiken, Newman, Phillips, and Bance (2011) demonstrated that the 8-Hz ASSR driven by a 4-Hz cycle change in interaural correlation of broadband Gaussian noise had the largest amplitude at 0 dB ILD for normal-hearing participants. However, the sound level was always fixed in one ear and the sound levels in the other ear were always equal to or lower than and not higher than the fixed reference level. Vanderydt (2017) included both positive and negative ILD stimuli and showed that the 40-Hz ASSR amplitude grew with increasing level in one ear and a fixed level in the other ear for 19 normal-hearing participants. The results are most likely due to the summed intensity across the ears, with the largest amplitudes evoked by stimuli with the largest positive ILD, and the smallest amplitudes evoked

by stimuli with the largest negative ILD, when keeping the level of one ear fixed.

Conclusions

In this study, 40-Hz ASSR amplitudes were used to estimate binaural loudness balance in participants with asymmetric hearing. Although good median results were found for participants with asymmetric hearing and for participants with bimodal hearing at apical CI channels, variability was also observed. Poor estimates were found for mid-CI channels. Better understanding of the cause of this variability is needed before ASSR amplitudes could be used as an estimate of the binaural loudness balance in clinical practice.

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