Frequency-dependent loudness balancing in bimodal cochlear implant users

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ABSTRACT

Conclusion In users of a cochlear implant (CI) and a hearing aid (HA) in contralateral ears, frequency-dependent loudness balancing between devices did, on average, not lead to improved speech understanding as compared to broadband balancing. However, nine out of 15 bimodal subjects showed significantly better speech understanding with either one of the fittings. Objectives Sub-optimal fittings and mismatches in loudness are possible explanations for the large individual differences seen in listeners using bimodal stimulation. Methods HA gain was adjusted for soft and loud input sounds in three frequency bands (0–548, 548–1000, and >1000 Hz) to match loudness with the CI. This procedure was compared to a simple broadband balancing procedure that reflected current clinical practice. In a three-visit cross-over design with 4 weeks between sessions, speech understanding was tested in quiet and in noise and questionnaires were administered to assess benefit in real world. Results Both procedures resulted in comparable HA gains. For speech in noise, a marginal bimodal benefit of 0.3 ± 4 dB was found, with large differences between subjects and spatial configurations. Speech understanding in quiet and in noise did not differ between the two loudness balancing procedures.

Introduction

Beneficial effects for the combined use of a cochlear implant (CI) and a contralateral hearing aid (HA) have repeatedly been reported [1]. Advantages provided through such ‘bimodal’ stimulation can include improved speech understanding in noise, voice pitch perception, localization abilities, and music perception [2–4].

Despite the overall positive findings, large individual differences in bimodal benefit have been found [1–3]. The factors that underlie these differences are not fully investigated, but may include, for example, tonotopical mismatches, degree of hearing loss and binaural fusion, sub-optimal fittings, and mismatches in loudness. An essential part of fitting is to obtain equal loudness percepts at both ears, but no well-validated bimodal fitting procedure is available to achieve this. Francart and McDermott [5] have proposed a model to normalize loudness through the CI and HA, aiming to achieve a loudness that is comparable to that in normal hearing. In the present study, we aimed at the more modest goal of achieving balanced loudness between both ears considering that, even if true loudness normalization cannot be achieved, the brain may still be plastic enough to extract binaural cues if loudness is balanced across input levels and frequencies [6].

Ching et al. [1] formulated a recommendation to achieve loudness balance between both devices in bimodal listeners for soft and loud input sounds, based on a pairwise comparison procedure with different HA frequency responses. However, other studies [7,8] have shown that not only the dynamic range differs between acoustically and electrically stimulated ears of bimodal listeners, but also the shapes of iso-loudness curves. Therefore, ideally, equal overall loudness would not only be achieved for soft and loud complex sounds, but for all signals across frequency bands.

Residual hearing in bimodal listeners is typically limited to the low frequencies, while most CI devices encode signals between 250–8000 Hz. Thus, adjusting HA gain to simply match the overall loudness of a broadband signal may result in loudness mismatches in frequency bands that are transmitted by only one device. In cases of low frequency residual hearing, over-amplification of the low frequencies by the HA is a likely result and a low frequency signal may be more appropriate for balancing. Ching et al. [9] balanced loudness in bimodally fitted children using a 65 dB SPL warble tone at 500, 1000, and 2000 Hz next to a paired comparison of several frequency responses deviating from the NAL prescription. Their findings highlight the importance of individual HA fine-tuning for optimized bimodal benefit, but the exact contribution of loudness balancing at different frequencies remained unclear.

In the present study, we investigated the effect of loudness balancing in three separate frequency bands: (1) low frequencies up to 500 Hz that contain voicing cues and complement information provided by the CI; (2) the middle frequency band (500 Hz–1 kHz) that potentially contains segmental...
information; and (3) the third band with frequencies above 1 kHz. We aimed to compare this frequency-dependent fitting procedure with a simple broadband loudness balancing procedure that reflected current clinical practice. A possible improvement in bimodal benefit of the new fitting method over the conventional approach was examined by testing speech understanding in quiet and in noise, and through subjective judgments.

**Methods**

**Subjects**

Fifteen post-lingual deaf subjects (10 male; mean age = 61 ± 12 years) participated in the study (Table 1). All used a Harmony speech processor (Advanced Bionics, Valencia, CA) in one ear, for at least a year. Subjects were selected with thresholds in the non-implanted ear better than 110 dB HL at 500 Hz. To eliminate variability due to devices, all subjects were fitted with one and the same type of compressive HA (Naida S IX UP, Phonak, Stäfa, Switzerland). However, the loudness balancing procedures investigated here were not specific for this product pair, but aimed to contribute to the general knowledge of bimodal fitting. Only six out of the 15 subjects were already bimodal users at the start of this study, but then used other types of HAs. The study was approved by the Local Ethics Committee of the Radboud University Nijmegen (protocol number 40327.091.12).

**Study design**

We compared a new bimodal hearing aid fitting protocol, which is referred to as ‘three-band fitting’, with the current clinical standard, referred to as ‘broadband fitting’. The study consisted of a three-visit cross-over design with 4 weeks between sessions (Figure 1). Subjects were randomly distributed over the two arms of the cross-over study in two groups without significant differences in hearing thresholds (Figure 2), age, gender, post-implant duration, and side of implant. Visits were scheduled on average 35 ± 6 days apart, with a minimum of 26 days, to allow for HA acclimatization during a take-home period.

**Set-up free field**

Sound stimuli for the broadband fitting and speech understanding tasks were delivered through an external soundcard.
(RME Babyface, Audio AG, Haimhausen, Germany), a main amplifier (MPA 4-80, Ecler, Spain) and JBL loudspeakers (Control 1, Harmon International Industries, Washington, DC). Free field presentation levels were calibrated using a sound level meter (Bruel & Kjaer 2260 investigator) at the position of the subject’s head. The calibration of the CI and the HA for stimuli presented through direct audio input (DAI) is described in the supplementary material.

**Hearing aid fitting procedures**

**General settings**

During the whole study, all adaptive features and settings were turned off in the CI and HA, except for the Naida’s adaptive feedback canceller in the case of feedback problems. The CI was left fixed at the subjects’ default everyday program and volume setting for both loudness balancing procedures. All HAs were fitted using in situ pure-tone audiometry through the HA. The HA fitting software (Phonak Target 3.0) allows to adjust HA gain in 20 small frequency bands. After loudness balancing, the HA gains in these bands were read out from the fitting software to compare both procedures. Both fitting procedures could be completed within a clinically acceptable 10–15 min and are described below.

**Broadband fitting**

The broadband fitting procedure was based on local clinical practice. Subjects were seated in a sound-treated room, 1 m in front of a loudspeaker. Nonsense natural running speech, adapted from the International Female Fluctuating Masker (IFFM) [10] was presented at 65 dB SPL. The fundamental frequency of the IFFM signal was lowered to 180 Hz, in-between a male and female voice (IFFM’), and a three-talker signal was created by overlaying different parts of the signal to make it slightly more steady-state (IFFM3’). Overall gain of the HA was increased or decreased, according to instructions of the subject, who was asked to find a balanced loudness with the CI, while listening to IFFM3’. The starting point was the conventional Phonak fitting rule (Adaptive Phonak Digital) [11].

**Three-band fitting**

The three-band fitting involved loudness balancing at two intensities (40 and 80 dB SPL) and in three frequency bands that could be adjusted separately in the HA fitting software: low (< 548 Hz), middle (548–1000 Hz), and high frequencies (> 1000 Hz). Loudness balancing was performed using a speech-shaped steady state noise, filtered according to the three frequency bands. Noise bursts of 1.5 s with ramps of 40 ms were presented alternately to the CI and HA via direct audio input (DAI), with an inter-stimulus interval of 0.6 s. Because of the short stimulus duration, steady-state noise was chosen instead of a speech signal to avoid large variations in loudness. The starting point was a novel fitting formula for bimodal fitting, which reduced gain to zero if the hearing loss exceeded 120 dB HL [12].

The HA fitting software allows for separate gain adjustments at three input levels: 40, 60, and 80 dB SPL. The HA gain for the soft (‘40 dB’ in the HA fitting software) and loud level (‘80 dB’) was adjusted separately per frequency band, until the subject reported to perceive a loudness balance across both ears. Loudness balancing was conducted sequentially from low-to-high bands and from soft-to-loud levels. To achieve a loudness balance for the 80 dB SPL input signal, the compression ratio of the HA was altered. Because the compression knee-point was set between 30–50 dB SPL input, depending on the hearing loss, this could in some cases affect the balance for soft sounds. When a loudness balance was achieved for all bands and levels, the IFFM3’ speech signal at 65 dB SPL was used in free field to check for a loudness balance using microphone input, which was always confirmed by the patient. Subjects were instructed not to use the volume control on their HA or CI during their take-home testing period.

To assess bimodal benefit after the take-home acclimatization period, measurements were performed as described below.

**Speech tests**

**Set-up**

Subjects were seated in a sound treated room with low reverberation. Three loudspeakers were positioned at a distance of 1 m from the patient’s head at 0°, +90°, and −90° azimuth.

Target words and sentences were always played via the loudspeaker directly in front of the subject at 0°.

For testing speech understanding in quiet, the NVA (Nederlandse Vereniging voor Audiologie) Dutch monosyllabic word test was used [13]. Words were presented at 65 dB SPL in three conditions: CI-only, HA-only, and CI + HA (bimodal). Per condition, three lists were presented and subjects were instructed to repeat the words as accurately as possible. The mean percentage phonemes correct was transformed to rationalized arc sine units (RAU) [14] for statistical analysis.

Speech understanding in noise was tested with the Leuven Intelligibility Sentence Test (LIST) [15]. Two types of noise were used: the speech-weighted noise provided by the LIST sentences, and the IFFM’ signal, referred to as single-talker noise. Noise was presented either from the front (S0N0), from the implanted side (S0NCl), the non-implanted side (S0NHA), or simultaneously from +90° and −90° (S0N ± 90). The S0N ± 90 configuration was tested with both noise types; S0N0, S0NCl, and S0NHA were only tested with single talker noise. All noise configurations were assessed under two listening conditions, CI + HA and CI-only, apart from S0N0, which was only evaluated for CI + HA.

The presentation level of the target sentences was held constant at 65 dB SPL, while the noise level was varied according to the standard scoring procedure of the LIST [15]. The first sentence of each list was presented at a 0 dB signal-to-noise ratio (SNR) and was repeated with decreasing noise level until correctly identified by the subject. Then, the noise level was changed adaptively in steps of 2 dB to obtain the 50% speech reception threshold (SNR 50), which was calculated as the mean of the last six SNRs (including one level
beyond the last presented). Two lists per condition were tested and the mean SNR50 was our final outcome measure.

The CI-only measurement was performed after another study in our lab with the same subjects, 2 months after the end of this study. Bimodal and HA-only conditions were measured for all sessions after the 4 weeks acclimatization period. Bimodal benefit was calculated by subtraction of the bimodal SNR50 from the CI-only SNR50, with higher values indicating more benefit. Listening conditions were always presented in random order within sessions.

**Questionnaires**

For each fitting, subjective evaluations were collected using the Speech, Spatial and Qualities of hearing scale (SSQ) questionnaire [16]. In addition, every week during the 4-week take home period, subjects were asked to fill in seven basic questions concerning everyday listening situations, to monitor adaptation. Both questionnaires were rated on a 0 (not good) to 10 (perfect) scale.

**Statistics**

Paired t-tests were used to compare HA gains after loudness balancing between both fittings, for each frequency band in each of the 40, 60, and 80 dB SPL input levels. Speech understanding and questionnaire results were analyzed using a Linear Mixed Model (LMM) treating ‘Subject’ as a random factor. For speech understanding in quiet, we used a fixed factor ‘Device’ (CI-only, bimodal-broadband, bimodal-three-band, HA-broadband, HA-three-band). Speech understanding in noise was tested per noise configuration with the factor ‘Device’ (broadband, three-band). Analysis per individual subject was done with a ‘Noise Configuration’ and ‘Fitting’ factor. For the questionnaire monitoring adaptation, an extra factor ‘Week’ (4 weeks) was included.

**Results**

**HA gain**

The mean difference in gain between fittings, after loudness balancing, is visualized in Figure 3 by the black dots. Broadband balancing resulted in more gain than three-band fitting with 40 dB SPL input for the middle (t(14) = 2.87, p = 0.01; BB: 62 ± 5 dB; 3B: 59 ± 5 dB) and high (t(14) = 3.89, p = 0.002; BB: 36 ± 4 dB; 3B: 20 ± 14 dB) frequency bands, but not for the low band. A similar result was found with 60 dB SPL input (middle band: t(14) = 2.24, p = 0.04; BB: 54 ± 6 dB; 3B: 51 ± 5 dB, high band: t(14) = 2.63, p = 0.02; BB: 25 ± 4 dB; 3B: 15 ± 13 dB). For the 80 dB SPL input level there were no differences in gain between fittings. Little gain was expected in the high frequency band of the three-band fitting because we eliminated gains at frequencies >120 dB HL. This effect is excluded in Figure 3 by the open symbols that represent gain differences only for frequencies where hearing loss was better than 120 dB HL. The 120 dB HL cut-off frequency was on average 3.1 ± 1.7 kHz and 1 kHz or higher for all subjects.

**Speech understanding in quiet**

Percentages of phonemes correct, transformed to rationalized arcsine units, differed significantly between listening conditions (F(4,56) = 122.44, p < 0.001) (Figure 4). The two HA-only scores (broadband: 19 ± 19 RAU; three-band: 20 ± 18 RAU) were worse than CI-only (84 ± 10 RAU, both p < 0.001) and both bimodal configurations (broadband: 97 ± 12 RAU; three-band: 84 ± 11 RAU, both p < 0.001).

**Speech understanding in noise**

Figure 5A shows the SNR50 of the CI-only and bimodal listening conditions and Figure 5B shows the difference between these values, called bimodal benefit. For none of the speaker configurations, a significant amount of benefit was found (S0N ± 90 stationary noise: F(1,14) = 0.01, p = 0.91; S0NHA: F(1,14) = 0.17, p = 0.69; S0NCi: F(1,14) = 0.79, p = 0.39; S0N ± 90 single-talker noise: F(1,14) = 0.05, p = 0.84). We also did not find a significant difference between broadband and three-band fitting (S0N ± 90 stationary noise: F(1,14) = 0.36, p = 0.56; S0NHA: F(1,14) = 0.06, p = 0.80; S0NCi: F(1,14) = 0.07, p = 0.79; S0N ± 90 single-talker noise: F(1,14) = 0.02, p = 0.89). Thus, overall, the HA did not bring an advantage nor disadvantage for speech understanding in noise, regardless of its fitting. The bimodal benefit, averaged over fittings, was 0.1 ± 4 dB for S0N ± 90.
Spatial release from masking

Spatial release from masking (SRM) represents the benefit from spatially separating the target and noise signals as compared to the S0N0 configuration. Only for S0NHA we found SRM (3.0 dB for both fittings) \( F(1,14) = 12.43, p = 0.001 \). For S0NCI, a significant decrement was found: \(-2.1 \text{ dB} \) \( F(1,14) = 15.21, p = 0.002 \). We obtained no significant difference between fittings (S0NHA: \( F(1,14) = 0.06, p = 0.80 \); S0NCI: \( F(1,14) = 0.07, p = 0.79 \)).

Questionnaires

We administered 30 questionnaires (two per subject), two of which were not returned. There were no significant differences between the broadband and three-band fitting in sub-sections of the SSQ: speech in quiet was given the highest ranking (7.0 for three-band fitting), but low rankings were given to speech in noise (4.3, broadband fitting) and other situations requiring the separation of multiple sources. Mean ratings, averaged over the two fittings, were 4.9 \( \pm \) 1.7, 4.3 \( \pm \) 1.6, and 5.6 \( \pm \) 1.4 for, respectively, the Speech, Spatial, and Quality domain. The questionnaire that was filled in every week to monitor the take-home period did not show any effects over time, implying no adaptation; three-band fitting was ranked significantly better for understanding one person in quiet \( F(1,93.54) = 7.00, p = 0.01 \) and the timbre of the sound \( F(1,89.10) = 7.74, p = 0.007 \); no difference was found for the other five questions (control of own voice, sound localization, perceiving speech intonation, understanding a group in quiet, and understanding one person at a party).

Factors correlating with bimodal benefit

No significant correlations were found between subject characteristics (the low (250, 500, 750, and 1000 Hz) and high (1, 2, 4 kHz) frequency pure tone average in the HA ear, age, bimodal experience, CI experience, electrical dynamic range, HA-only phonemes correct scores) vs the amount of bimodal benefit averaged over fittings or vs the difference in benefit of both fittings.

Discussion

In this study, a loudness balancing procedure was tested for the combined use of a CI and HA, which was intended to balance loudness between devices across the dynamic range and across frequencies. This three-band fitting procedure was compared to a simple balancing procedure using a broadband signal. The two procedures differed in stimulus type (speech vs stationary noise), frequency band (broadband vs three bands), input level (65 dB SPL vs both 40 and 80 dB SPL) and stimulus presentation (free field vs DAI). By these

in stationary noise, \(-0.2 \pm 5.0 \text{ dB for S0N} \pm 90 \text{ in single-talker noise, } 0.9 \pm 4.0 \text{ dB for S0NCI and } 0.3 \pm 4.0 \text{ dB for S0NHA.}

Figure 6 shows the individual bimodal benefit for the two fittings, averaged over the two SNR50’s measured per condition. Significantly more benefit for one of the fittings was found for nine out of 15 subjects. Five subjects did 3.1 \( \pm 1.0 \text{ dB} \) better on average with the broadband fitting (P1, P4, P7, P11, P15) and four subjects showed 3.3 \( \pm 1.2 \text{ dB} \) more benefit with the three-band fitting (P2, P6, P9, P12). Of note, after Bonferroni correction for multiple comparisons, reducing the level of significance to \( p = 0.05/15 \), the results of only one subject remained significant (P6, \( p = 0.003 \)). The trends towards individual differences seemed not related to the subject’s binaural experience; most subjects reported to perceive only minor differences between both

fittings. However, we noted that the subjects that performed better with the broadband fitting had more bimodal experience than the four subjects that performed better with the three-band fitting (see Discussion).
speech understanding when amplified [17]. The additional gain corresponding to dead regions that can sometimes hamper speech understanding in the case of usable high-frequency residual hearing. Another reason can contribute to improved speech understanding in the case of better high frequency thresholds (S0NCI: more benefit from three-band as opposed to broadband fitting). This finding was supported by a trend towards more benefit with either one of the fittings for higher frequencies, but these probably started of this study. Of the other group, better with three-band, only one subject was an experienced bimodal user. Possibly, bimodal performance was biased towards the broadband fitting, since HA fittings of the experienced bimodal users corresponded more with the broadband than with the three-band fitting. The 4-week adaptation period we applied in our cross-over design was possibly not long enough for full acclimatization to the new bimodal listening situation, with a fully fused sound percept and pitch match with the CI [18]. The absence of large differences in bimodal benefit between both fitting procedures is possibly explained by the similarity in HA gains after loudness balancing (Figure 3), especially for the lower frequencies. This implies that the standard Phonak fitting formula we used for broadband fitting resulted in a frequency response with a low frequency slope that agreed well with loudness judgments of our subjects. We did find a significant difference in HA gain between fittings for higher frequencies, but these probably played a minor role in speech understanding, given the severe hearing loss of our subjects.

**Bimodal benefit**

Bimodal benefit was on average 0.4 dB with noise from the HA side (S0NHA) and 0.9 dB for S0NCI. For adult bimodal listeners, values of, respectively, 1 dB and 1–3 dB have been reported in the literature [1,4,19], and our results are, therefore, comparatively small. However, so far we have not mentioned that we performed a CI-only measurement before we provided subjects with their new HA, besides the CI-only measurement at the end of the study; bimodal benefit was on average 0.4 dB with noise from the non-implanted ear vs the additional benefit from three-band balancing (three-band minus broadband) in the S0NCI noise configuration. White markers identify subjects that benefited significantly more from broadband balancing, and grey markers identify subjects that benefited significantly more from three-band balancing. (subjects with black markers did not benefit significantly more with either one of the fittings).

Another finding regarding individual differences is that all five subjects who seemed to perform better with the broadband fitting did have experience with wearing a HA beside their CI and four of these five were still bimodal users at the start of this study. Of the other group, better with three-band, only one subject was an experienced bimodal user. Possibly, bimodal performance was biased towards the broadband fitting, since HA fittings of the experienced bimodal users corresponded more with the broadband than with the three-band fitting. The 4-week adaptation period we applied in our cross-over design was possibly not long enough for full acclimatization to the new bimodal listening situation, with a fully fused sound percept and pitch match with the CI [18].

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benefit (but at the risk of under-estimation, e.g. in the case of a content-learning effect of the sentences that had to be re-used for the final CI measurement).

Single-talker non-sense speech was a more effective masker than stationary speech-weighted noise. The absence of a positive effect of masker modulations in speech understanding in noise in CI users has recently been interpreted as the result of spectral smearing caused by current spread, leveling out masker modulations [20]. Considerable spatial release from masking was only present when noise was shifted from the front to the HA side and a deteriorating effect occurred by moving the noise source to the CI side, consistent with findings from others [3]. This was not an unexpected finding since the head shadow protects the CI ear from high frequency noise components in the S0NHA configuration, while low frequencies remain more or less audible at the HA ear. For speech in quiet we did not find a change in performance by adding a HA, in line with several other studies testing bimodal subjects with comparable poor residual hearing [4,19].

Subjects reported to perceive the pitch of the signal used for loudness balancing differently in each ear, especially for the highest frequency band in three-band fitting. The maximum possible amplification of the HA was insufficient for establishing a loudness balance in this frequency band (>1 kHz) for five subjects (no link could be found with the bimodal performance of these subjects). For future studies, we would, therefore, recommend to reduce the bandwidth to frequencies with hearing loss below 120 dB HL, ensuring better audibility. The procedure can, furthermore, be improved by an additional compression knee point in between the soft and loud level, to allow for free gain adjustments.

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Disclosure statement
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