Acta Acustica 2024, **8**, 5

https://doi.org/10.1051/aacus/2023066

Available online at:
https://acta-acustica.edpsciences.org

SCIENTIFIC ARTICLE

OPEN ACCESS

Visualization and analysis of multi-channel dynamic range compression in hearing aids

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Received 28 February 2023, Accepted 8 December 2023

Abstract – One main functionality of hearing aids is restoring audibility. This means that low sound pressure levels are amplified above the elevated hearing threshold, and higher sound pressure levels do not exceed the individual uncomfortable loudness level (UCL). To this end, hearing aids provide frequency-dependent dynamic range compression which is denoted as hearing aid channels (HACs) in the recently published standard IEC 60118-16. As an increasing number of HACs, among other features, is one main feature to differentiate between price or technology levels, IEC 60118-16 includes a measurement procedure to verify the number of HACs. In this work, we verify this test procedure with a research hearing aid (RHA), and evaluate six commercial hearing aids of three different manufacturers and two technology levels. These results demonstrate the possibilities and limitations of the new test procedure. Furthermore, we introduced an extension of this test procedure with a channel-specific compression setting to overcome limitations and to get a deeper insight into the functionality of HACs in hearing aids. These results show that many HACs of commercial devices are coupled to neighboring frequencies, and that different strategies are used across manufacturers to adapt the number of HACs for different technology levels.

Keywords: Hearing aid channel (HAC), Automatic gain control (AGC), Dynamic range compression, Compressor

1 Introduction

Modern hearing aids provide various features to compensate for hearing deficits. The main intention is to make sounds audible, better and easier understandable, or to increase comfort [1–4]. Restoring audibility is an intrinsic feature of hearing aids, which is basically realized by providing frequency-specific gain and dynamic range compression often, referred to as hearing aid channels (HACs) [1–6]. In the new standard IEC 60118-16, a HAC is defined as a "feature of the signal processing of a hearing aid that enables individual adjustment of the gain and the parameters of an automatic gain control for a certain frequency range" [6]. There are two main reasons why a frequency-dependent fitting of compression and gain is required: (i) the real ear insertion gain (REIG) strongly depends on individual factors such as the anatomy of the ear canal, the mechanical impedance of the ear drum, and the selected hearing aid coupling; (ii) the auditory dynamic range, which is the range between the hearing threshold and uncomfortable loudness level [7], is frequency-dependent for most hearing impairments. A frequency-specific adjustment of gain only, which is denoted as "hearing aid band" in IEC 60118-16, is insufficient for the compensation of most hearing impairments due to the frequency-dependent auditory dynamic range. While the audiological need for HACs is generally agreed, there are differing views on the appropriate resolution in frequency, i.e., the appropriate number of HACs [8–10]. For the evaluation, speech intelligibility [11, 12], the speech intelligibility index (SII) [13], the possibility for loudness equalization [13], the accuracy of meeting fitting targets [14], or vowel identification [15] were considered. Most studies show that a significant improvement can be noticed for an increase up to 4–8 HACs for common types of hearing loss. People with a steep sloping audiogram seem to require more HACs than people with a flat and moderately sloping audiogram [8]. Further increasing the channel number has a negligible effect or can have even negative effects [11, 15].

Although the appropriate number of HACs is not clear, the number increases with technology level or price category for almost all commercially available hearing aids. Furthermore, in some tenders or national regulations, a minimum number of HACs is defined, e.g., in Germany the public health insurance requires at least 6 HACs to get reimbursement [16]. Beside other features, a higher

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number of HACs is a main argument for higher prices of hearing aids. Hence, there is a valid interest in being able to verify the number of HACs without having access to internal tools of the manufacturer, e.g., a developer software, which has been addressed in [5] and IEC 60118-16 [6]. The basic principle of [5] and [6] is comparable, i.e., a sine tone at a higher sound pressure level triggers the compression at a dedicated frequency and the effect of the compression is measured with a broadband noise at a lower sound pressure level. No development software or a dedicated test program is required. The realization is different, Kates used adaptive filters [5], and IEC 60118-16 considers fractional octave sound pressure levels [6]. In this work, we focus on the procedure of IEC 60118-16, only. It includes not only a test procedure, but also the definitions of hearing aid channels and bands mentioned above.

The main goal of this work was to present the concept of the measurement procedure of IEC 60118-16 and to demonstrate its possibilities and limitations. Moreover, a modification of the procedure with a channel-specific compression setting was introduced to overcome limitations of the basic procedure. A research hearing aid (RHA) where the characteristics of the HACs are known in advance was tested as reference with the basic and modified procedure to evaluate the reliability of the measurement results. Then, the functionality of HACs in six commercial hearing aids from three different manufactures were analyzed with the basic and modified procedure. From each manufacturer a device with medium and high technology level was included and compared to each other.

2 Methods

2.1 Measurement procedure

According to IEC 60118-16 [6], a sine tone at an elevated level was used to trigger the compression at a dedicated frequency. At the same time a broadband pink noise was presented to detect the frequency range where the compression was active. Since the procedure of IEC 60118-16 is based on fractional octave band levels, pink noise has the advantage that each fractional octave band carries an equal amount of energy, which leads to a comparable measurement accuracy across frequency. The standard suggests limiting the bandwidth of the pink noise to 0.2–5 kHz, 0.2–8 kHz, or 0.1–10 kHz. We have used 0.1–10 kHz. For the test, the hearing aid were configured with a broadband or channel-specific compression setting as explained in Section 2.2. For the main measurement, first, a pink noise with 1/12 octave band levels of 44 dB SPL was presented to the hearing aid and the 1/12 octave band levels at the output were stored as reference. Then, a superposition of the same soft pink noise and a sine tone at 70 dB SPL was presented to the hearing aid. Again, the 1/12 octave band levels at the hearing aid output were measured. As shown in panel (a) of Figure 1, the sine tone at a higher level of 70 dB SPL triggers the compression in a certain frequency range which results in decreased 1/12 octave band levels for these frequencies compared to the reference values (see Fig. 1 panel (b)). The peak around the sine frequency can be replaced by an interpolation between the neighboring 1/12 octave band levels (see Fig. 1 panel (c)), which was stored in one column of a two-dimensional result matrix. This procedure was successively repeated for 68 sine tones at all 1/12 octave center frequencies between 200 Hz and 8 kHz according to IEC 61260-1 [17]. For the evaluation of the output signals, the 1/12 octave band levels at the same center frequencies were considered so that the result matrix has a quadratic size of 68 × 68. Furthermore, to evaluate the number of independent HACs according to IEC 60118-16, which is discussed in Section 3.1, the cut-off frequencies of the gain reduction were determined with a threshold of −3 dB as visualized in panel (d) of Figure 1. Furthermore, a threshold of −2 dB was used for the channel-specific compression setting as explained in Section 2.2.

2.2 Hearing aid settings

First, the hearing aids were programmed with the Functional Test Setting (FTS) according to IEC 60118-16 [6]. This means all accessible features in the fitting software were manually disabled and a linear gain was applied equally to the Reference Test Setting (RTS) according to IEC 60118-0 [18]. Then, according to IEC 60118-16, dynamic range compression was activated in all HACs so that a soft pink noise with a 1/12 octave band level of 44 dB SPL was processed linearly, whereas a 70 dB SPL sine sweep experienced a gain reduction of at least 5 dB over the whole frequency range considered. The input-output characteristics of a HAC can usually be configured by changing parameters such as compression ratio (CR) and knee-point, or gains for different input levels. However, this can be different among manufacturers. Hence, IEC 60118-16 defines a minimum amount of gain reduction of 5 dB.

To make sure that the gain reduction was solely caused by dynamic range compression and not by the output limiter of the hearing aid, it was checked whether the 1/12 octave band levels measured were at least 5 dB below the OSPL90 curve [18]. After this check, the desired broadband compression setting was obtained.

One goal of this work was to investigate the contribution of each single HAC available in the fitting software to the broadband multi-channel signal processing. For this purpose, the configuration was modified. Instead of a broadband compression a channel-specific compression was configured successively for each HAC. This means compression was only active for the HAC under consideration, and all other HACs were programmed with a linear gain setting. For each HAC, the sine tones at all test frequencies were evaluated which results in a 68 × 68 matrix for each HAC available in the fitting software.

2.3 Measurement setup

All measurements were performed inside an anechoic test box (Brüel & Kjær, Type 4232) including a

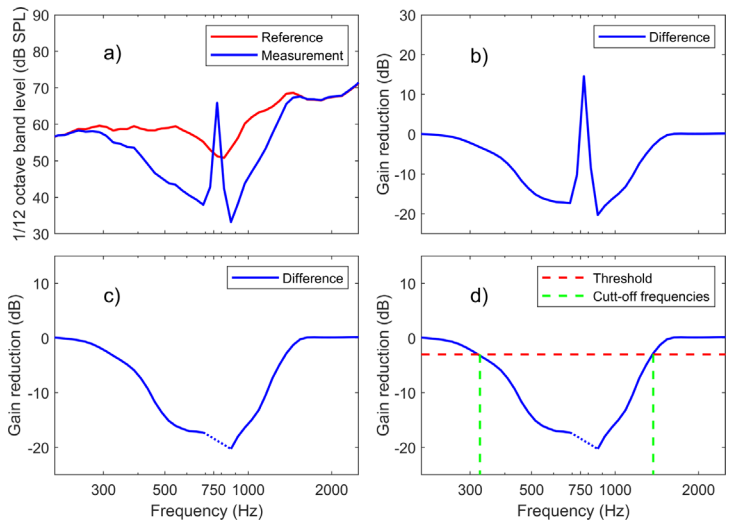

Figure 1. Illustration of the measurement procedure of IEC 60118-16 [18].

loudspeaker, a coupler microphone and a reference microphone (both Brüel & Kjær, Type 4192). The input and output signals of the test box were generated and recorded with a PC using Matlab and an RME fireface UC sound card. The coupler microphone was equipped with a 2 cm^3-coupler according to IEC 60318-5 [19]. Since the frequency range of the 2 cm^3-coupler is limited to 8 kHz, the test frequencies and the analysis of the output signals were also limited to 8 kHz as mentioned before.

2.4 Research hearing aid (RHA)

As reference, the measurements were performed with a RHA. As hardware, the Portable Hearing Lab (PHL) was used, which is a portable miniature PC (Beagle Bone Black) with a 6-channel audio interface and the opportunity to connect realistic behind the ear hearing aid headsets with external receivers [20]. Due to its small size in combination with the hearing aid headsets, the RHA could be tested identical to commercial hearing aids [21]. As software, the open Master Hearing Aid (openMHA) was selected, which is an open source, PC-based software platform that offers real-time audio signal processing [22]. It was used to build up an 8-channel compressor. Applying the settings of Section 2.2 yielded in a CR of 1.9. The channels were implemented by a weighted sum of short-time Fourier transform (SFTF) bins, based on Hann windows with a length of 480 samples (zero-padded to 1024) at 24 kHz. The 8 channels were constructed with an equal frequency spacing on a logarithmic scale between 150 Hz and 6 kHz (see Fig. 2). The spectral weighing of each channel was 1 across half its frequency width around the center frequency, and decreased linearly (for a linear magnitude and logarithmic frequency axis) around it such that it reached 0.5 at the central point towards the neighboring channel's center frequency. For the highest and lowest channels, the spectral gain remained at 1 up to the highest and lowest of the STFT bins, respectively.

2.5 Commercial hearing aids

In this study, six different behind-the-ear (BTE) hearing aids of three different manufacturers were tested. For each manufacturer, a device of medium and high technology level of the hearing aid series of 2021 was included. Applying the settings of Section 2.2 yielded in a CR of >2, but the exact value was not documented. The number of HACs, which were available in the corresponding fitting software and which lay within the considered frequency range between 200 Hz and 8 kHz, are listed in Table 1.

3 Results

3.1 Verification of the number of independent HACs

The numbers of independent HACs of each hearing aid tested were determined as described in IEC 60118-16 [6]. The evaluation was based on the measurement results achieved with the broadband compression setting (see Sec. 2.1). For each test frequency the lower cut-off frequency (LCF) and the upper cut-off frequency (UCF) were determined (Fig. 1 panel (d)). This means for each test frequency it was checked in which frequency range the reduction in 1/12 octave band gain was equal to or below a threshold of −3 dB. The lowest 1/12 octave center frequency that still fulfilled this condition was stored as the LCF, the highest was chosen as the UCF. Table 2 shows example results of lower and upper cut-off frequencies derived for different test frequencies. The selected test frequencies correspond to the center frequencies of the HACs as denoted in the fitting software of manufacturer A's medium technology level (*Man A med*). In a next step, the numbers of different LCFs and UCFs were counted. The higher of these two numbers is considered as N_{TA}, which is the minimum number of independent HACs theoretically available according to IEC 60118-16. Then, a comparison between the N_{TA} and the number of HACs available in

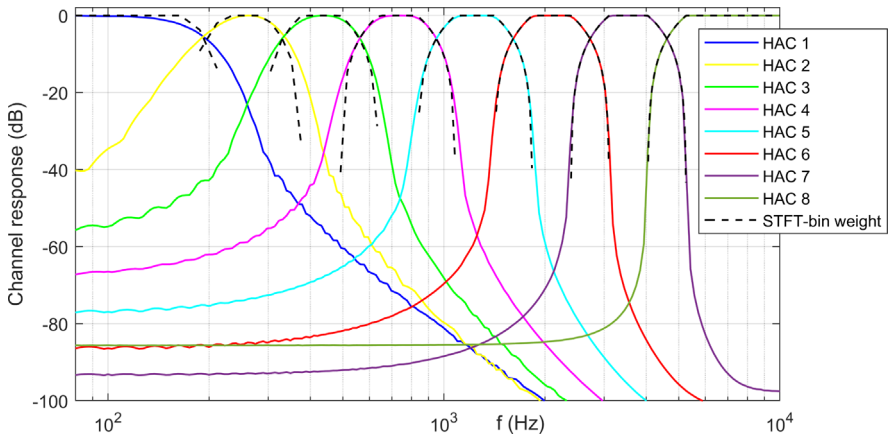

Figure 2. Input bandpass filters of the eight hearing aid channels (HACs) of the research hearing aid (RHA).

Table 1. Number of HACs available in the fitting software for the three manufacturers and two technology levels (TLs) considered. The number in brackets indicates all HACs and the number without brackets only those within the considered frequency range of 200 Hz to 8 kHz.

	Number of HACs	
	Med. TL	High TL
Manufacturer A	11 (12)	17 (20)
Manufacturer B	10 (10)	19 (20)
Manufacturer C	10 (10)	15 (15)

Table 2. Example results of the evaluation of the number of independent hearing aid channels for the medium technology level of manufacturer A.

Test frequency (Hz)	LCF (Hz)	UCF (Hz)
183	183	434
244	183	729
487	183	1155
729	244	1728
972	434	2054
1223	613	2304
1631	818	3255
2304	1155	4340
3073	1454	6879
4097	1939	8175
5788	2901	8175
	9 different frequencies	10 different frequencies

the fitting software (N_{FS}) results in a final statement about the number of independent HACs (N_{IHACs}):

- if $N_{\mathrm{FS}} \leq N_{\mathrm{TA}}$, it is stated that $N_{\mathrm{IHACs}} = N_{\mathrm{FS}}$,
- if $N_{\mathrm{FS}} > N$, it is stated that $N_{\mathrm{IHACs}} \geq N_{\mathrm{TA}}$.

If all 68 test frequencies (see Sec. 2.1) were considered for the evaluation of N_{IHACs}, very high numbers of different upper and lower cut-off frequencies were detected (see Tab. 3). As a consequence, N_{TA} is almost twice as high as the N_{FS} for each tested hearing aid. Eventhough, the final statement about N_{IHACs} yields correct numbers for all devices, the large deviations between N_{TA} and N_{IHACs} indicate limitations of the verification procedure regarding a high number of test frequencies.

Table 3. Resulting number of independent hearing aid channels N_{IHACs} considering all 68 test frequencies.

	N_{LCFs}	N_{UCFs}	N_{TA}	N_{FS}	N_{IHACs}
RHA	26	24	26	8	8
Man A med	27	28	28	11	11
Man A high	28	33	33	17	17
Man B med	35	37	37	10	10
Man B high	35	36	36	19	19
Man C med	31	33	33	10	10
Man C high	35	39	39	15	15

In Table 4 the number of test frequencies used for the verification procedure was reduced to the number of HACs available in the fitting software for each hearing aid. The chosen test frequencies correspond to the center frequencies denoted in the fitting software. For the RHA, the procedure now yields accurate results with matching numbers of N_{TA} and N_{FS}. For the commercial hearing aids, the deviations between N_{TA} and N_{FS} were also much smaller. However, N_{TA} now tends to underestimate N_{FS} by one or two HACs in all cases. The lower N_{TA} occurs due to repetitive LCOs at low test frequencies and repetitive UCFs at high test frequencies, as exemplary shown for *Man A med* in Table 2. Similar findings were also observed for all other commercial hearing aids and are likely caused by the limitation of the frequency range from 200 Hz to 8 kHz.

3.2 Visualization

For the visualization, the result matrices for the broadband compression setting were converted into grayscale plots, as shown in Figure 3. To this end, each matrix element is represented by a colored square in the *xy*-plane.

Table 4. Resulting number of independent hearing aid channels N_{IHACs} considering only the center frequencies denoted in the fitting software.

	N_{LCFs}	N_{UCFs}	N_{TA}	N_{FS}	N_{IHACs}
RHA	8	8	8	8	8
Man A med	9	11	10	11	≥10
Man A high	13	15	15	17	≥15
Man B med	9	9	9	10	≥9
Man B high	17	18	18	19	≥18
Man C med	9	9	9	10	≥9
Man C high	12	13	13	15	≥13

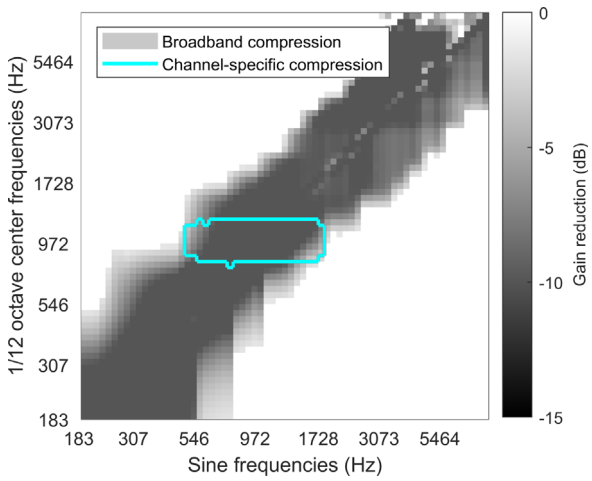

Figure 3. Example of combining results measured with broadband and channel-specific compression for the medium technology level of manufacturer A and hearing aids channel 5. The grayscale plot represent the results measured with broadband, and the blue contour the results measured with channel-specific compression.

The color of each square depends on the corresponding gain reduction measured. Gray squares show a gain reduction due to compression, whereas white squares indicate linear processing. One column represents the measurement result at one test frequency (see Fig. 1d). This means the x-axis represents the test frequency of the sine tone, and the y-axis indicates the center frequencies of the 1/12-octave-bands where the output signal was evaluated.

To combine the results measured with a broadband and a channel-specific compression, contours were created around the areas of gain reduction measured with a channel-specific compression. The contours encircle the area of gain reduction equal to or below a certain threshold. Contrary to the definition in IEC 60118-16, the applied threshold was chosen to be −2 dB instead of −3 dB, since this modification yielded a more accurate graphical representation of the individual HACs for the commercial devices. These contours were then pasted into the grayscale plot of the the results measured with a broadband compression setting (see example in Fig. 3). In this way, the contribution of the individual HACs available in the fitting software to

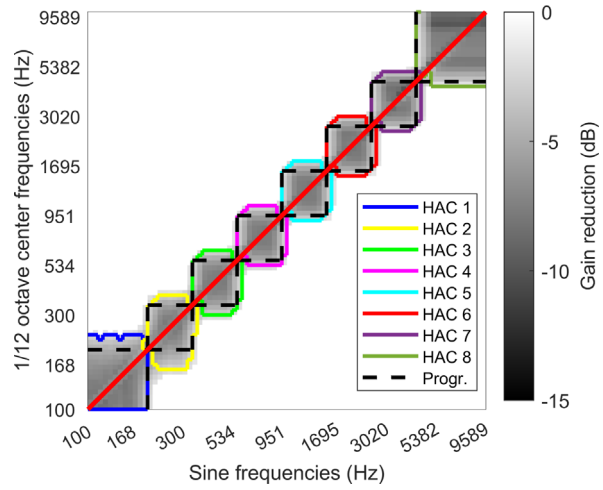

Figure 4. Grayscale plot for the broadband compression results of the research hearing aid (RHA). Additionally, the channel-specific results are visualized with colored contours, and the cut-off frequencies of the programmed hearing aid channels (HACs), which are also depicted in Figure 2, are indicated with black dashed contours.

the broadband multi-channel signal processing of the hearing aids were visualized.

3.2.1 Results of the research hearing aid (RHA)

The results measured with the RHA are shown in Figure 4. The gray area, representing the result with broadband compression, is axisymmetric to the bisecting line, and shows a contour similar to stair steps. The contours achieved with a channel-specific setting well match the contour of the gray area. This indicates identical excitation and compression ranges of the individual HACs in both configurations. In other words, the compression in each channel acts independently. Moreover, the clear stair-step-like shape makes it easy to distinguish individual HACs, even if the contours of the results with a channel-specific compression setting were not inserted. The areas of gain reduction of an individual HAC is shaped approximately like a square, which indicates an identical frequency range where the compression is triggered and where it is effective. Additionally, there is only very little overlap between the areas of gain reduction of the individual HACs. This means a certain frequency triggers mostly only the compression of one specific HAC.

As the cut-off frequencies of the HACs within the RHA are well-known, it is also possible to draw conclusions regarding the accuracy of the measurement procedure. For this purpose, the programmed and known cut-off frequencies were additionally inserted into Figure 4 as black dotted lines. A comparison with the contours achieved with a channel-specific compression setting shows only marginal deviations. These deviations are likely due to measurement tolerances and the different threshold of −2 dB chosen for the measurements with a channel-specific compression

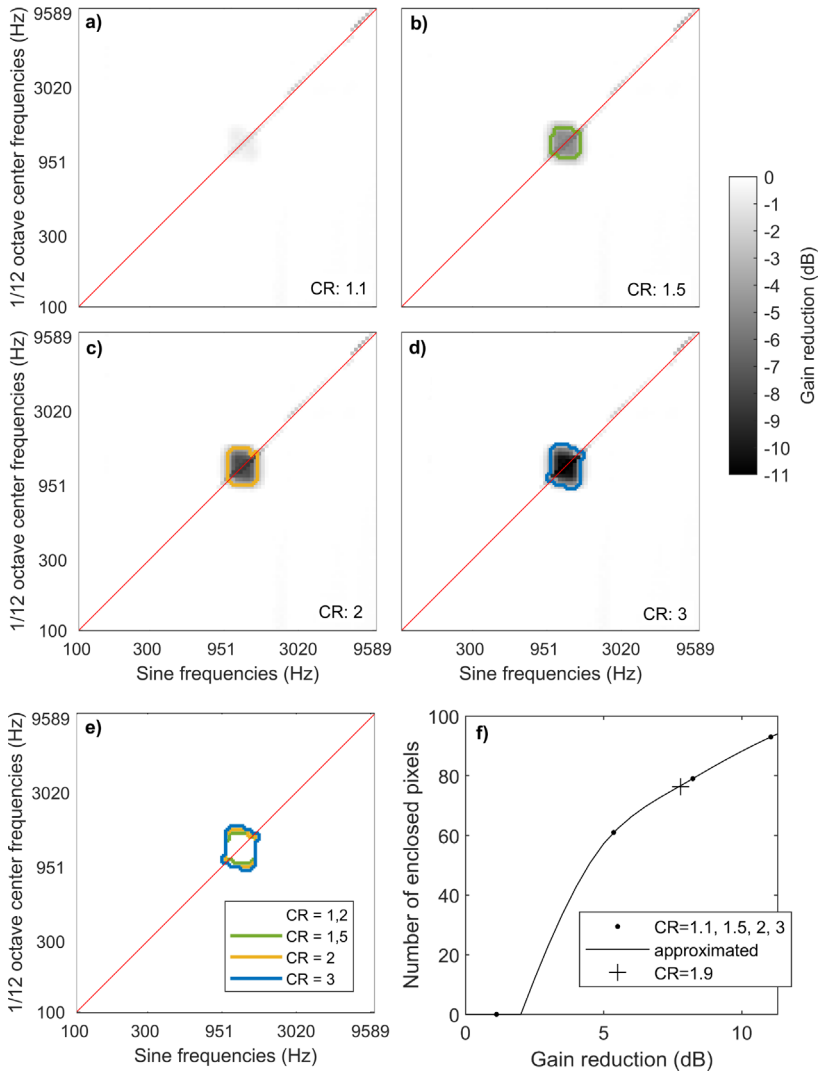

Figure 5. Grayscale plot and the contours detected for a channel specific compression of hearing aid channel 5 (HAC 5) of the research hearing aid (RHA). Panel (a)–(d) show the results for different compression ratios (CRs), and panel (e) depicts all contours detected within one plot. In panel (f), the number of pixels enclosed by the contours is plotted against the amount of gain reduction due to different CRs.

setting. A threshold of −3 dB would reduce the height of the areas of gain reduction measured with a channel-specific setting (see Fig. 1d), and would probably lead to even smaller deviations.

Furthermore, the RHA was used to investigate the influence of the amount of gain reduction on the measurement results. For this purpose, compression was activated in HAC 5 only and a CR of 1.1, 1.5, 2, and 3 was programmed, which led to a different amount of gain reduction. In Figure 5, panel (a)–(d) shows the results for each CR. The comparison of all contours detected shows that the amount of gain reduction has an influence on the size of the areas measured, and the effect is stronger in y-direction (see panel (e) of Fig. 5). In panel (f) of Figure 5, the number of pixels enclosed by the contours is plotted against the amount of gain reduction due to different CRs. Since a reduction of 2 dB is used for the channel-specific measurement as threshold, a contour can be detected only for a gain reduction above this threshold. To visualize this effect, an approximated curve has been plotted in in panel (f) of Figure 5. Above the threshold of 2 dB, this curve is based on a shape-preserving piecewise cubic interpolation. This plot reveals that the impact on the size of the areas detected is very high for a gain reduction slightly above threshold. Clearly above threshold, the size of the areas detected seems to linearly increase with the amount of gain reduction.

3.2.2 Results of the commercial hearing aids

In Figure 6, the results for the medium technology levels of the commercial hearing aids are depicted for all three manufacturers. As for the RHA, the colored contours representing the results with a channel-specific compression setting match the contour of the gray area representing

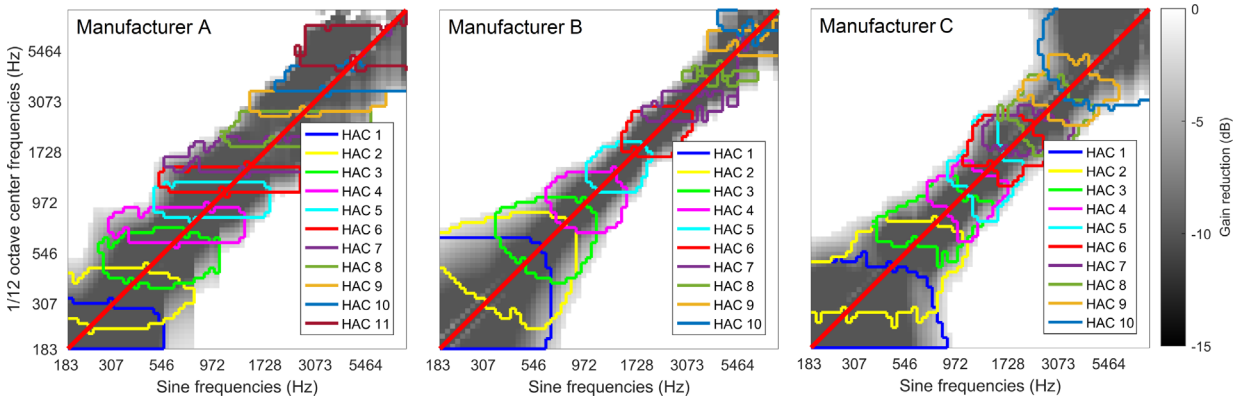

Figure 6. Combined results of the broadband and the channel-specific compression setting for the medium technology level of manufacturer A, B, and C.

the results achieved with a broadband compression setting in most cases accurately for all three manufacturers. But at low frequencies (<1 kHz), there are some bright-gray colored regions within the broadband compression results of all three manufacturers that are not covered by the contours of the individual measurements. There are also other noticeable differences compared to the RHA. On the one hand, the gray areas do not show sharp edges but look more like smooth tubes. Hence, it is difficult to identify the contribution of individual HACs within the results with broadband compression without the contours of the measurements with a channel-specific compression. In addition, differences between the three manufacturers could be observed. For *Man A med*, the gray tube has an almost constant width over the whole frequency range, whereas it decreases towards higher frequencies for *Man B med*, or has a smaller width at medium frequencies for *Man C med*. On the other hand, the amount of overlap between the HACs is much larger compared to the results of the RHA for all manufacturers. E.g., for *Man A med*, a test frequency at 1700 Hz triggers five different HACs, i.e., almost half of the total umber of HACs. Another difference can be found in the shapes of the individual HACs. For *Man B med*, the shapes of HACs at low and medium frequencies can be roughly approximated as squares, whereas the bottom left corner is missing (see HAC 2 and 3 in Fig. 6b). HACs at high frequencies of *Man B med*, as well as all HACs of *Man A med* can be geometrically approximated as horizontal rectangles. Moreover, for *Man A med*, the horizontal rectangles getting flatter and wider towards higher frequencies. This horizontal rectangular shape implies that the frequency range where the compression is active is smaller compared to the frequency range where the compression is triggered. In addition, it means that the compression in one HAC is also triggered by neighboring frequencies, which are not affected by the compressed of this HAC. In the results of *Man C med*, the contours of several individual HACs are shaped approximately like crosses, e.g., see HAC 5 in Figure 6c. It means that the frequency range where the compression is effective decreases, if it is triggered at frequencies further away from the center frequency of the HAC.

3.3 Comparison of technology levels

As the measurements were not only performed with a medium technology level but also with high technology level devices of the same hearing aid series for each manufacturer, the technology levels of each manufacturer were compared to each other. Regarding the measurement with a broadband compression setting, contours were created around the gray, tube-like shaped areas of gain reduction in the results of both technology levels. Those contours were than both inserted into one plot to visualize differences and similarities between the broadband measurements of both technology levels. For manufacturers A and B, the contours of both technology levels were almost congruent over the whole frequency range with only marginal deviations, as shown for in Figure 7. The same comparison is illustrated for manufacturer C in Figure 7. Here, an almost congruent shape of both contours can be observed for medium frequencies in the range of 900–3000 Hz as well. However, for frequencies below and above this range there were noticeable differences between the contours of both technology levels, as the area of gain reduction is narrower for the high technology level device.

The technology levels of the three manufacturers were further compared using the results of the channel-specific compression settings. Again, contours were drawn around the areas of gain reduction, but this time individual for all channel-specific settings. Comparing the contours of all HACs of both technology levels leads to three different observations:

- The contour of one HAC in the medium technology level was congruent with the contour of one HAC of the high technology level device (see case 1 in Fig. 8).
- The combined contours of multiple HACs in the high technology level device yielded clearly the contour of one HAC in the medium technology level (see case 2 in Fig. 8).
- The contours showed noticeable differences, no congruence was found for one HAC of the medium technology level and one or more HACs of the high technology level device.

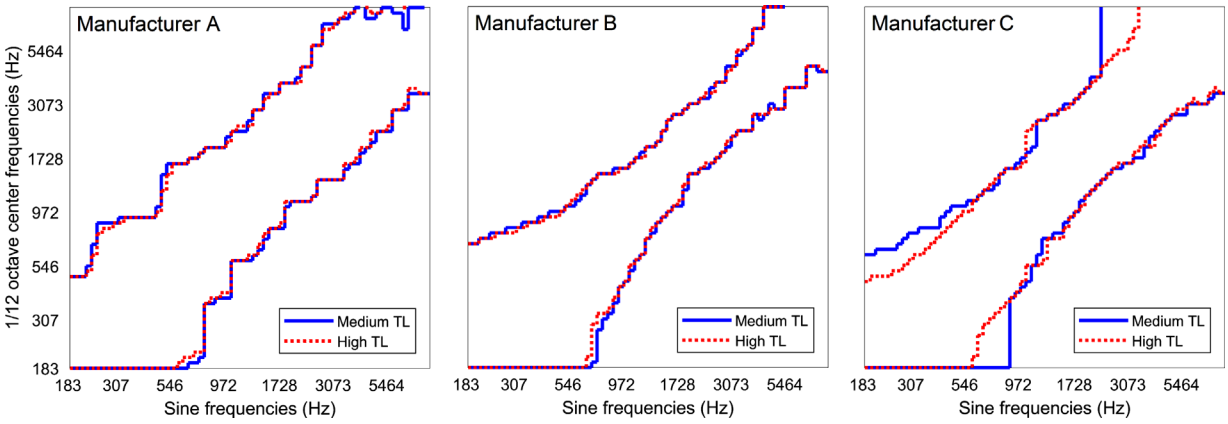

Figure 7. Comparison of contours of the broad band measurement results between the high and medium technology level of manufacturer A, B, and C.

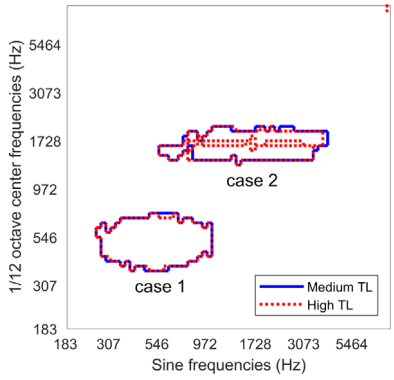

Figure 8. Examples for the relation of hearing aid channels (HACs) between medium and high technology level measured with channel-specific compression.

The results of this channel-specific comparison are illustrated in Figure 9 for all three manufacturers. For each manufacturer, the row indicates which HAC of the medium technology level has the largest overlap with one or multiple HACs of the high technology level. If one or multiple HACs of the higher technology level could be clearly mapped to one HAC of the medium technology level either as shown in case 1 or in case 2 of Figure 8, they are marked with the same color as the HAC of the medium technology level. If no mapping between both technology levels could be found, the cell of the HAC of the high technology level is left white.For manufacturer A, congruence could be detected for all HACs within the considered frequency range between 200 Hz and 8 kHz.

For manufacturer B, all HACs of the medium technology level were congruent with either one or a combination of several HACs of the high technology level. However, there were also some HACs (HAC 1, 5, 7, 10, 15 and 17) of the high technology level device in between, for which no congruence to the medium technology level was found. The HACs of manufacturer C show congruence between the technology levels in the medium frequency range. For low- and high frequency HACs no congruence has been observed.

4 Discussion

4.1 Measurement procedure

In our study, the determination of the number of HACs according to IEC 60118-16 was most accurate, if the center frequencies of the HACs denoted in the fitting software were selected as test frequencies. However, the actual number of HACs was slightly underestimated (see Tab. 4). We assume that this underestimation occurred due to the limited frequency range of 200 Hz to 8 kHz, since cut-off frequencies outside this range could not be distinguished (see Tab. 2). Hence, increasing the frequency range seems to be a solution to overcome this shortcoming. In this case, it is suggested to use no 2 cm^3-coupler, which has a upper frequency limit at 8 kHz according to [19]. An alternative could be an ear simulator according to IEC 60318-4 [23] or a 0.4 cm^3-coupler according to IEC 60318-7 [24], which allow reliable measurements up to 16 kHz.

Beside, the limited frequency range, there are further limitations. First, the underlying number of HACs is independent of the technology level for some manufacturer so that the measurement result show no differences between technology levels (see manufacturer B in Fig. 7). Thus, the measurement results alone cannot be used to distinguish between technology levels. Second, the individual HACs are very difficult to distinguish in measurement results with a broadband compression setting. Although the corresponding center frequency of a HAC are used multiple HACs can be triggered so that not the cut-off frequencies of the intended HAC is detected (e.g., see Fig. 6). Therefore, it is difficult to directly link the results with a broadband compression setting to individual HACs available in the fitting software and to determine their effective frequency ranges. Third, due to measurement tolerances, an increased number of test frequencies leads to a higher number of different cut-off frequencies and thus to a higher number

Manufacturer A	
Med. TL	High TL
HAC 1	HAC 1
HAC 2	HAC 2
HAC 3	HAC 3
HAC 4	HAC 4
HAC 5	HAC 5
HAC 6	HAC 6
HAC 7	HAC 7
	HAC 8
HAC 8	HAC 9
	HAC 10
	HAC 11
HAC 9	HAC 12
	HAC 13
HAC 10	HAC 14
	HAC 15
HAC 11	HAC 16
	HAC 17

Manufacturer B	
Med. TL	High TL
HAC 1	HAC 1
	HAC 2
HAC 2	HAC 3
HAC 3	HAC 4
	HAC 5
HAC 4	HAC 6
	HAC 7
HAC 5	HAC 8
	HAC 9
HAC 6	HAC 10
	HAC 11
	HAC 12
HAC 7	HAC 13
	HAC 14
	HAC 15
HAC 8	HAC 16
	HAC 17
HAC 9	HAC 18
HAC 10	HAC 19

Manufacturer C	
Med. TL	High TL
HAC 1	HAC 1
	HAC 2
HAC 2	HAC 3
	HAC 4
HAC 3	HAC 5
	HAC 6
HAC 4	HAC 7
HAC 5	HAC 8
HAC 6	HAC 9
HAC 7	HAC 10
HAC 8	HAC 11
HAC 9	HAC 12
HAC 10	HAC 13
	HAC 14
	HAC 15

Figure 9. Mapping of hearing aid channels (HACs) between medium and high technology level (TL) of manufacturer A, B, and C. The row indicates which HAC of the medium TL has the largest overlap with one or multiple HACs of the high TL. If one or multiple HACs of the higher TL could be clearly mapped to one HAC of the medium TL, they are marked with the same color as the HAC of the medium technology level. If no mapping between both TLs could be found, the cell of the HAC of the high TL is left white. The number of HACs available in the fitting software within the considered frequency range are listed in Table 1.

HACs (see Tab. 3). To overcome these problems, IEC 60118-16 requires that also the number of HACs available in the fitting software needs to be considered (see Sec. 3.1). This approach helps that no unrealistic number of HACs is stated but it is no direct prove of the functionality of an individual HAC available in the fitting software. Hence, the broadband measurements according to IEC 60118-16 should be understood more as a plausibility check.

As shown in this study, measurements with one HAC active at a time could be a possible adaptation of the measurement procedure to clearly demonstrate the functionality and effective frequency range of each HAC available in the fitting software. Results with the RHA precisely matched the known frequency ranges of the HACs (see Fig. 4) which verifies the accuracy of this approach. However, channel-specific measurements significantly increase test time and require a manual adjustment of hearing aid settings during the measurements. Consequently, one should carefully consider whether these extended measurement possibilities justify the increased effort.

4.2 Shapes of the areas of gain reduction

Measurements with the RHA reveal that the amount of gain reduction programmed has an influence on the size of the areas detected. If the gain reduction is below the threshold of 2 dB, no contours can be detected, e.g., as for a CR of 1.1 in panel (a) of Fig. 5. The size of the areas of gain reduction increases with increasing CR. This effect is stronger in y-direction (see panel (e) of Fig. 5), probably due to the evaluation of the thresholds in this direction. Moreover, the impact is very high for a gain reduction slightly above threshold. Clearly above threshold, the size of the areas detected seems to linearly increase with the amount of gain reduction. Hence, if the width of a HAC should be precisely measured, the amount of gain reduction used for testing should be defined.

Different shapes, such as squares, rectangles and crosses, were measured for the areas of gain reduction. A square means that the frequency range where the compression can be triggered is equal to the frequency range where it is effective. This is most intuitive but was only observed

for the RHA (see Fig. 4) and for a few HACs of the commercial devices, e.g., the lowest HAC of *Man B med* in Figure 6. The most frequent shape that could be observed, e.g., for the HACs at higher frequencies of manufacturer B and all HACs of manufacturer A, were horizontal rectangles with a wider excitation range compared to a smaller effective range of compression. Since neighboring frequencies outside the effective range of a HAC also influencing the compression, this shape can be understood as a channel-coupling between neighboring HACs. The channel-coupling is used to preserve natural spectral contrasts within phonemes, which have been proven to be important for speech intelligibility [2, 15].

Other HACs of *Man B med* show a square-like shape but with missing corners. These missing corners are even more pronounced for the cross-like shapes measured for the individual HACs of manufacturer C (Fig. 6). These artifacts can be explained by the input band-pass filters of HACs, e.g., as shown for the RHA in Figure 2. The finite slope of the filter functions leads to a smooth transition from stop to pass-band. If a sine tone is presented further away from the center frequency, its level is reduced which leads to less compression in the corresponding HAC. Furthermore, a smaller reduction in gain may also shift the cut-off frequencies determined towards the center frequency (see Fig. 1), which causes the missing corners.

4.3 Differences between technology levels

The comparison of the results achieved with the broadband compression setting showed identical results for both technology levels of manufacturer A and B (see Fig. 7), although the number of HACs available in the fitting software is different. These findings indicate that the underlying number of HACs of manufacturer A and B is equal for different technology levels and that the number of adjustable HACs available in the fitting software is adapted only. Furthermore, the results indicate that the way how HACs available in the fitting software are reduced for the medium technology level is different among manufacturers. A manufacturer can reduce the specified number of HACs in a lower technology level by linking gain and compression across channels while using the same filterbank as in the higher technology level, reducing the number of frequencies at which gain and compression can be specified while keeping the higher-level filterbank, or using a filterbank with fewer HACs.

For manufacturer A, HACs are identical or multiple HACs of the high technology level are combined to one HAC in the medium technology level (see left panel of Fig. 9). All HACs of the high technology level are also visible in the medium technology level, e.g., HAC 9–11 of the high technology level are merged to HAC 8 in the medium technology level and can only be configured together.

For manufacturer B, also some HACs are equal and some of the high technology level are merged in the medium technology level (see Fig. 9). In addition, there are HACs of the high technology level that could not be mapped to HACs of the medium technology level indicated as white cells in Figure 9. Since the measurement results with a broadband compression setting show the same areas of gain reduction, it seems unlikely that a different spectral processing is used for both technology levels. A possible explanation could be that those "white" HACs are automatically configured depending on the setting of the neighboring HACs. If the compression is only active in one HAC, this leads to no visible compression in a "white" HAC. Another explanation could be that these HACs are simply deactivated in the medium technology level, but due to the overlap with neighboring HACs the broadband contour is not changed.

The comparison of the medium and high technology level of manufacturer C reveals that HACs in the medium frequency range between 900 Hz and 3000 Hz are equal, and at lower and higher frequencies no mapping could be found (see right panel of Fig. 9). A similar results can be seen for the results with broadband compression where the contours are slightly different at lower and higher frequencies (see Fig. 7). Hence, we assume that a different frequency-specific processing is used for the medium and high technology level.

5 Conclusion

The procedure defined in IEC 60118-16 can clearly show the effect of frequency-depended dynamic range compression, but it cannot prove the functionality of individual HACs available in the fitting software. As an alternative, a procedure with channel-specific compression settings was introduced, and verified using a RHA with known compression settings. The channel-specific procedure gives deep insights into the frequency-dependent dynamic range compression and its relation to compression settings available in the fitting software. These results reveal that many HACs of commercial hearing aids are coupled to neighboring HACs. For this purpose, the frequency range triggering the compression is wider than the frequency range where the compression is effective. Furthermore, the channel-specific measurements show different strategies to adapt the number of HACs between technology levels. For two manufacturers, it seems that the underlying number of HACs is equal between technology levels, and the settings available in the fitting software are adapted, only. On the contrary, the results of one manufacture suggest that HACs with different cut-off frequencies are used for different technology levels.

Conflict of interest

Authors declared no conflict of interests.

Data availability statement

Data are available on request from the authors.

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Cite this article as: Jürgensen L. Denk F. & Husstedt H. 2024. Visualization and analysis of multi-channel dynamic range compression in hearing aids. Acta Acustica, **8**, 5.