

Advantages of a non-linear frequency compression algorithm in noise

Andrea Bohnert · Myriell Nyffeler · Annerose Keilmann

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Abstract A multichannel non-linear frequency compression algorithm was evaluated in comparison to conventional amplification hearing aids using a test of speech understanding in noise (Oldenburger Satztest—OLSA) and subjective questionnaires. The new algorithm compresses frequencies above a pre-calculated cut off frequency and shifts them to a lower frequency range, thereby providing high-frequency audibility. Low-frequencies, below the compression cut off frequency, are amplified normally. This algorithm is called SoundRecover (SR). In this study, 11 experienced hearing aid users with a severe to profound sensorineural hearing loss were tested. Seven subjects showed enhanced levels of understanding in noise (OLSA) using frequency compression. However, 4 out of the 11 subjects could not benefit from the high-frequency gain. Evaluation using questionnaires demonstrated an increased level of satisfaction after 2 months of experimental devices wearing ($p = 0.08$) and after 4 months of wearing ($p = 0.09$), respectively, compared to conventional hearing instruments.

Keywords Profound hearing loss · High-frequency audibility · Multichannel non-linear frequency compression algorithm · Speech understanding in noise · Subjective questionnaires

Introduction

Speech is based on lower frequencies, representing the main zone of consonants, resonating overtones (formants) of vowels and high consonants which constitute the so called sibilant sound (/s/,/f/,/z/,/sh/). For most hearing losses, the primary goal of amplification is to provide a sufficiently audible speech signal. People with a significant hearing loss have difficulties hearing high-frequency speech information, such as /f/,/s/, and /sh/[13]. In numerous languages/s/is known to be linguistically one of the most important fricatives. Bandwidth of current hearing instruments is wider than ever before, nevertheless high-frequency gain in conventional hearing instruments drops off above 5 kHz. That means the upper limit of frequency is below the peak frequencies of /s/spoken by female and child talkers [17]. Stelmachowicz et al. [16] showed that for male talkers the optimum performance was reached at a bandwidth around 4–5 kHz; whereas for the female and child talkers it was not reached until a bandwidth of up to 9 kHz.

The greater the hearing loss, the more gain needs to be applied at these high frequencies to achieve audibility. However, in many cases hearing sensitivity is so poor in the high frequencies that it is technically not possible to increase the gain sufficiently to achieve audibility. The gain can be limited by acoustic feedback, discomfort resulting from excessive loudness or the output abilities of the amplification system. Furthermore, in some cases, even when high-frequency information can be made audible, it may not be discriminated due to irreversible damage to the hair-cell receptors in the inner ear. However, it still remains unclear why only a subgroup of subjects with a profound to severe hearing impairment benefit from sufficient high-frequency

A. Bohnert (✉) · A. Keilmann
Department of ENT and Communication Disorders,
Mainz Medical School, Langenbeckstr. 1,
55131 Mainz, Germany
e-mail: bohnert@kommunikation.klinik.uni-mainz.de

M. Nyffeler
Phonak AG, Laubisrütistrasse 28, 8712 Stäfa, Switzerland

amplification, whereas others do not [4, 5]. One possible explanation may be the existence of the so called dead regions [10, 11]. Previous studies revealed that subjects with a profound to severe hearing impairment but without dead regions significantly benefited from high-frequency amplification, whereas subjects with dead regions did not [1, 20].

As conventional amplification does not provide sufficient high-frequency amplification, the alternative of shifting high-frequency sounds to lower regions, where audibility is available could serve as a viable alternative. Various frequency shifting algorithms have been developed over the years, whereby large differences in implementation, resulting sound quality and potential speech understanding benefits have been found between the different approaches [8, 9]. These signal processing strategies often used linear modulation techniques for frequency shifting or transposition [6–9, 12, 14, 15, 18, 19].

Method

Subjects

Fourteen hearing-impaired adults, 6 women and 8 men (age: 17–76 years; average age: 51.5 years), participated in the study. The majority of the subjects had severe to profound hearing loss. Their hearing threshold levels, measured conventionally under headphones, are listed in Table 1. All subjects had a sensorineural hearing loss as shown by standard air and bone conduction audiometry and tympanometric evaluation (Table 1). The target hearing loss range has been selected between 250 and 4,000 Hz with a decreasing slope of hearing threshold level above 40 to 60 dB HL and an uncomfortable loudness threshold of 100–120 dB HL. Whereas the target was to include subjects with a binaural symmetrical SNHL, one subject had an unaidable ear and thus was fit monaurally. Further, complete absence of or not sufficient speech development has been considered as exclusion criteria.

Audiological assessment

Before fitting the new experimental frequency compression device, pure-tone audiometry including measurements of air (AC) and bone (BC) conduction threshold, as well as threshold for uncomfortable loudness level (UCL) were conducted followed by speech audiometry with numbers and monosyllables. Additionally, tympanometry and stapedial reflex were measured.

Experimental device

The experimental devices were behind-the-ear (BTE) digital power instruments (experimental devices of Phonak Naída) with a maximum of 140 dB output and 80 dB maximal gain (2 cc and Ear Simulator coupler), respectively. The experimental device makes use of a non-linear frequency compression algorithm which is called Sound-Recover (SR). This algorithm extends the audible range by compressing and shifting inaudible high frequencies into an area with audible hearing. The algorithm compresses frequencies above a programmable cut off frequency and shifts them to lower frequencies, whereas the low frequencies are amplified without frequency compression. A cut off frequency between 1.5 and 4 kHz and the compression factor between 1.5:1 to 4:1 can be chosen. The gain and amplitude compression characteristics were separately adjustable in five partially overlapping frequency bands.

Fitting of experimental device

Depending on the user's experience level, a first fit to pre-calculation, has been performed with the Phonak fitting software (iPFG version 1.7). Beside the feedback canceller, all noise reduction systems were turned off, bass boost was not applied and all instruments were set to have an omnidirectional microphone. The occlusion manager was adjusted to the desired subjective level and the start-up program was set to quiet.

Frequency compression test

To fit the frequency compression device, an experimental graphic user interface has been developed for the Phonak fitting software (iPFG version 1.7). It allows the comparison of different frequency compression settings using a touch screen, where equal loudness level measurements were used to fit the frequency compression device in quiet. Buttons with a random spatial distribution for each subject are connected to the different frequency compression settings, where one was the control condition (neutral) plus seven different pre-sets of frequency compression settings. For this specific testing, subjects were seated at a distance of 1 m in front of a loudspeaker. Continuous speech (male and female voice) was presented from a CD at the level of 65 dB HL. Hence, subjects were allowed to listen to all settings as often as they wanted and were then asked to rate all settings compared to the neutral setting. Ratings were given on a scale of 1 to 15, where 1 was “much worse than neutral”, 8 was “as good as neutral” and 15 was “much better than neutral”. Further, the setting with the maximum

Table 1 Hearing threshold levels (dB HL) and selected cut off frequencies for the subjects who participated in the study

		Frequency (kHz)										Selected cut off frequency (kHz)
Subject	Ear	0.25	0.5	0.75	1	1.5	2	3	4	8		
S1	L	90	100	100	100	95	90	85	75	95	3,000/3	
	R	80	85	80	80	80	75	80	80	75		
S2	L	70	80	80	85	80	80	80	85	80	2,000/2	
	R	65	70	75	80	85	85	70	75	65		
S3	L	65	65	70	75	75	75	80	70	50	2,000/3	
	R	65	70	80	85	80	80	80	80	60		
S4	L	40	60	60	65	85	110	105	105	105	2,000/1;5	
	R	40	60	65	70	80	90	110	105	105		
S5	L	55	55	65	75	85	>110*	>110*	>110*	105	1,500/1;5	
	R	40	45	50	65	75	90	90	110	>110*		Abruption
S6	L	70	80	85	90	95	95	110	>110*	>110*	2,000/3	
	R	75	80	80	80	85	85	95	100	105		
S7	L	70	80	100	105	105	>110*	>110*	>110*	>110*	2,000/3	
	R	40	45	45	45	65	70	70	70	70		Abruption
S8	L	20	35	55	65	85	100	105	110	>110*	2,000/3	
	R	20	45	55	65	90	105	110	110	>110*		
S9	L	60	70	70	70	75	85	100	110	>110*	2,000/3	
	R	70	70	70	70	75	85	95	105	>110*		
S10	L	20	40	50	60	70	75	80	80	65	2,000/3	
	R	25	40	55	60	75	85	100	>110*	>110*		
S11	L	30	45	45	45	70	75	75	70	90	3,000/3	
	R	50	60	65	65	70	70	75	80	85		
S12	L	55	55	60	65	65	75	70	90	85	3,000/3	
	R	80	80	75	75	75	80	105	110	>110*		Abruption
S13	L	85	75	70	70	70	75	90	110	>110*	2,000/3	
	R	60	50	55	55	70	75	80	90	100		
S14	L	35	55	65	80	>110*	>110*	>110*	>110*	>110*	3,000/3	

Note that asterisks indicate levels which were limited by the maximum output of the audiometer

rating was enabled and pre-set automatically in iPFG version 1.7.

Frequency compression settings were adjusted and fine-tuned, if necessary, at the follow-up sessions. The cut off frequency was chosen individually for each subject based on the data of the frequency compression test.

Verification of hearing instruments (HI)

Hearing instrument verification was based on the desired sensation level input/output formula (DSL [i/o]) method for both devices, the own hearing instrument and the experimental device. Before fitting the new device, probe-tone measurements were obtained to verify the adjustments of the subjects own hearing instruments. All fine-tunings made with the frequency compression device were also verified with the DSL method.

Speech comprehension

The Oldenburger Sentencetest (OLSA, [21]), an adaptive speech test, comprises 40 lists with 30 non-sense sentences composed of 5 real words (name–verb–number–adjective–object) which are divided into three blocks of 10 sentences each. Test subjects were seated in the middle of a circle of loudspeakers and were asked to focus the loudspeaker at 0° Azimuth, where speech signal and noise were presented. Background noise consisted of the same long-term spectrum as the speech material and was presented at constant 65 dB. In contrast to the constant background noise, speech signal was varied based on the standardized adaptive method described by Wagener et al. [21]. This test measures the speech-reception-threshold (SRT). The speech tests were conducted with the subjects own hearing instrument and with the experimental device.

Questionnaires

Two different questionnaires were used in the study to get subjective data on general benefit and sound quality of the experimental device compared to the own HI. Both questionnaires were developed for this study. One questionnaire was used right after the initial fitting of the experimental device and was called “spontaneous acceptance”-questionnaire. Six questions about sound quality and two questions evaluating the overall impression of the new algorithm were asked. The second questionnaire used in the study was called “real life test questionnaire”. This questionnaire was handed out by the audiologist after each session for the home trial period. Subjects were asked to critically compare their own current HI to the new experimental devices. The “real life questionnaire” consisted of four subgroups of questions—sound quality, loudness, usefulness in noisy situations and speech intelligibility in quiet and in noise. Each subgroup contained 7 questions, as for example: “Does sound appear too loud”, “Does sound appear too sharp”, “Does sound appear too shrill”, “How was your benefit in noisy situations”, “How is the sound of your own voice”, “How is the sound of voices of other persons”, “How much do you understand in noisy surroundings”, “How much strain do you have by understanding speech in noisy surroundings”, etc.

For both questionnaires the scale reflected five different categories of satisfaction. These categories were: much worse than own HI, less than own HI, as good as own HI, better than own HI, much better than own HI. These five categories were subdivided into 15 sections in total. Each of these subsections was rated with a value between 0 and 100%.

Study protocol

During the first assessment, the hearing aid usage, the medical history and the electro-acoustic characteristics of each subject’s own hearing instruments was documented (Table 2). Additionally, a pure-tone audiogram, including air and bone conduction, was obtained. Speech intelligibility tests (OLSA) were performed with the subjects own HI. Then, each subject was fitted with identical experimental hearing instrument model with the frequency compression turned off.

The cut off frequency was chosen individually for each subject based on the data of the frequency compression test. Subjects were advised to judge both their own HI and the experimental device by responding to the “spontaneous acceptance” questionnaire. After fitting, test subjects were asked to wear the experimental device in their daily life and to complete questionnaires at four follow-up sessions

(Fig. 1). During each assessment, subjects were given a speech in noise test (OLSA, [21]). If necessary, fine-tuning was performed during these sessions. No further adjustments were made to the program for the remainder of the trial. The choice of multiple assessments also allowed the observation of a developmental acclimatization to the new devices.

Statistical analysis

Speech reception thresholds (SRT) in the OLSA were depicted for each subject and reported without statistical analysis.

Questionnaires were used to obtain subjective data of speech intelligibility in quiet and noise as well as for general benefit and sound quality of the experimental devices which were compared to the own HI. Ratings evaluating speech intelligibility ranged from “nothing” to “all”, those of overall impression from “very unsatisfied” to “very satisfied” and those of sound quality from “very uncomfortable” to “very comfortable”. Ratings were labelled with a number where negative ratings obtained a lower number and positive ratings had a higher number. The percentage shown in Figs. 3 and 4 were calculated as follows: [(given rating × 100)/total rating possible]. Mean values of percentages over single subjects of the different conditions were analysed using independent Student’s *t* tests (two-tailed). Statistical significance was set at $p < 0.05$. Analyses were conducted using the statistical software SPSS (version 16.0) implemented on a personal computer running the Windows XP operating system.

Results

Fourteen hearing impaired adults participated in the study. As much as 3 out of these 14 subjects discontinued the participation for several personal reasons, so finally 11 test subjects remained. One subject could not accept the experimental prototypes, another subject stopped participating because of a case of death in the family and one subject showed complete absence of or not sufficient speech development which has been considered as exclusion criteria. For 7 out of these 11 subjects, the new non-linear frequency compression algorithm provided superior satisfaction. Compared to the conventionally fitted hearing aids understanding of speech in noise was also ameliorated. Furthermore, it is important to note that experimental devices were held in an omni directional modus to that sound as well as noise of all directions were included in amplification. To examine only the new algorithm the experimental device which was a high power device did not contain a directional microphone, a beamformer and a

Table 2 Age and aetiology of HL of the test subjects, types and features of the conventional hearing devices used before experimental device fitting

Subject	Age (years)	Probable aetiology of hearing loss	Type of own hearing aids	Features of own hearing aids	Processing strategy of conventional hearing device	Ears fitted
S1	30	Hereditary hearing loss	Phonak PicoForte PP-C-P	Analogue	Linear	Binaural
S2	17	Congenital hearing loss	Phonak Supero 411	Digital	Non-linear	Binaural
S3	45	Hereditary hearing loss	Phonak Savia 311	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural
S4	52	Progressive hearing loss, unknown genesis	Siemens Signia	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural
S5	60	Progressive hearing loss	Siemens Acuris P	Digital	Non-linear	Binaural abruption
S6	76	Unsystemic dizziness, hearing loss, progressive	Phonak Claro 311 dAZ	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural
S7	65	Hearing loss, unknown genesis	Siemens Artis P	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural abruption
S8	24	Congenital hearing loss, progressive	Siemens Prisma P	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural
S9	67	Hearing loss with the age of 52, progressive	Phonak Savia 311/Widex ITE	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural
S10	60	Progressive hearing loss	Siemens Infinity Pro	Digital	Non-linear	Binaural
S11	58	Hearing loss, unknown genesis	Phonak Savia 311	Fully automatic digital aid with adaptive directional microphone	Non-linear	Binaural
S12	49	Progressive hearing loss	Audioservice Aumea PMC-ITE	Digital	Non-linear	Binaural abruption
S13	55	Hearing loss, unknown genesis	Audioservice Aumea 184 (Kind 1 122)	Analogue	Linear	Binaural
S14	63	Progressive hearing loss, unknown genesis	Phonak Savia microPower	Fully automatic digital aid with adaptive directional microphone	Non-linear	Left

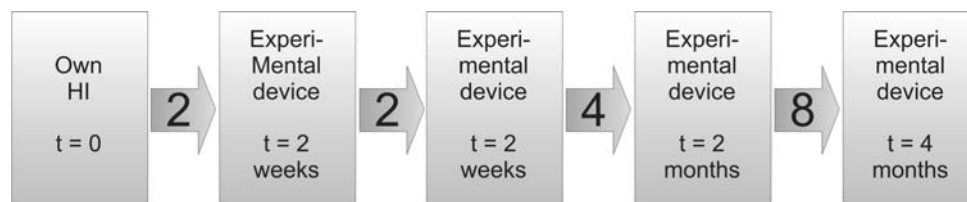


Fig. 1 Test schedule. After rating of own HI and performance of audiological diagnostic, patients were fitted with the experimental HI equipped with sound recover, fitted with the preferred setting. In the

following assessments audiological debriefings were performed and follow-up questionnaires were handed out

noise canceller. In contrast, it has been seen that all test subjects used their own HI with more of these features activated improving subjective satisfaction and speech intelligibility. All test subjects very well fitted in high-frequency ranges as before.

Speech intelligibility

The SRT in the OLSA for all subjects is given in Fig. 2. The dark grey bars show the results with the subjects own

HI and the light grey bars show the results for the experimental devices at the last visit. Subject 6 experienced highest improvement of -7.35 dB SRT (reduction of SRT) followed by subjects 13 and 14 with -4.35 dB and -2.20 dB SRT. Subject 8 showed an improvement of -3.05 dB, subject 10 an improvement of -2.85 dB and subjects 1 and 11 showed only slight improvements of -0.25 and -0.3 dB. As much as 4 subjects out of 11 showed a deterioration of performance in the OLSA. Subject 2 delivered the highest deterioration being 7.85 dB

SRT, whereas subject 3, 9 and 4 showed only a deterioration of 2.5, 2.45 and 1.15 dB SRT, respectively.

Questionnaire

According to the test schedule patients answered questionnaires (Figs. 3, 4).

As shown in Fig. 3 test subjects were split into two groups—those who benefited subjectively and those who did not profit from the new device. This split was seen in all questions resulting in a similar picture in all panels of Fig. 3. For understanding in quiet (panel 3a), patients 4 and 9 rated the new device much better (35% and 23.5%, respectively). The mean value of the subgroup of satisfied users increased significantly after 2 ($p < 0.01$) and 4 ($p < 0.05$) months.

Although patients reported fricatives to sound unnatural most patients reported a more satisfying sound quality in quiet. For the subgroup of satisfied users the mean value increased after 2 ($p < 0.05$) and 4 ($p < 0.05$) months. As for the understanding of speech, patients 2, 3 and 10 were not satisfied (panel 3b). Most patients, especially patient 4, reported the experimental devices easier to wear (panel 3c), in the subgroup of satisfied users this was more pronounced in quiet ($p < 0.05$ after 2 and 4 months) than in noise ($p = 0.08$ after 2 months and $p = 0.09$ after 4 months). Again for patients 2, 3 and 10 the ratings were worse, because for them the experimental device was more tiring to wear. The rating of the overall usefulness (Fig. 3) was similar to the results of the more detailed questionnaire (Fig. 2). Overall impression of the frequency compression algorithm, depicted in panel 4b, was rated very positively especially in test subjects 4 (66% higher than conventional HI), 9 (33% higher) and 14 (20% higher than conventional ones) it was very satisfactory. Therefore, mean values of satisfaction of the new algorithm were significantly different from conventional HI either after 2 ($p < 0.05$) or after 4 months ($p < 0.05$) of testing.

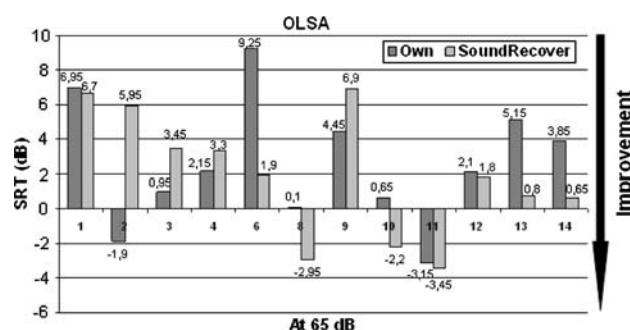


Fig. 2 Speech reception threshold (SRT). Dark grey bars show the results with the subjects own HI and light grey bars show the results for the experimental device at the last visit

Discussion

Proceeding field studies with the new algorithm have shown restoration of high-frequency audibility, spontaneous user acceptance, quick acclimatization and improvements of own voice quality [2] Recently, Simpson et al. [15] reported a significant score improvement in recognition of monosyllabic words using an experimental frequency compression hearing device in quiet. Similar to our study, frequency compression was performed by compressing a high-frequency range which is then shifted to an adjacent lower-frequency area, thereby providing audibility of high frequencies. They suggested that some of the improvements may have resulted from the better audibility provided in the high frequencies by the experimental device in comparison with the conventional aids. However, a subsequent study [15] showed that increasing the high-frequency gain in the conventional aids did not produce equivalent perceptual benefits.

Similar to our study, the frequency compression scheme used in the above-mentioned study aimed to provide high-frequency speech cues, while preserving the low-and mid-frequency components of speech. Thus, speech understanding in quiet significantly improved using the experimental device. While McDermott et al. [9] compared percentages of phonemes and/or consonants as well as fricatives and/or vowels correctly identified between quiet situations, we determined the SRT and compared levels of satisfaction while using a non-linear frequency compression algorithm in quiet and in noise. As described above, the non-linear frequency compression algorithm resulted in a significant increase of satisfaction both in a quiet and in a noisy situation, after 2 months of experimental hearing device usage. However, as McDermott [8] mentioned, it could not be excluded that some feedback oscillation occurred with the additional high-frequency gain program wherewith in our study; negative satisfaction level of the new algorithm might be explained.

The non-linear frequency compression algorithm effectively extends the audible range by compressing and shifting inaudible high frequencies into an adjacent area with audible hearing, whereas lower frequencies are amplified and processed by the hearing instrument without frequency compression. The initial frequency compression setting is automatically calculated, based on an audiogram of the better ear, for each hearing instrument user during fitting.

We found that the new algorithm improved the SRT in 7 out of the 11 subjects (Fig. 2). Furthermore, non-linear frequency compression positively impacted subjective rating of sound quality as well as the effort to wear the HI both in quiet and in noisy situations (Fig. 3). Taken together, the new algorithm resulted in more satisfaction and

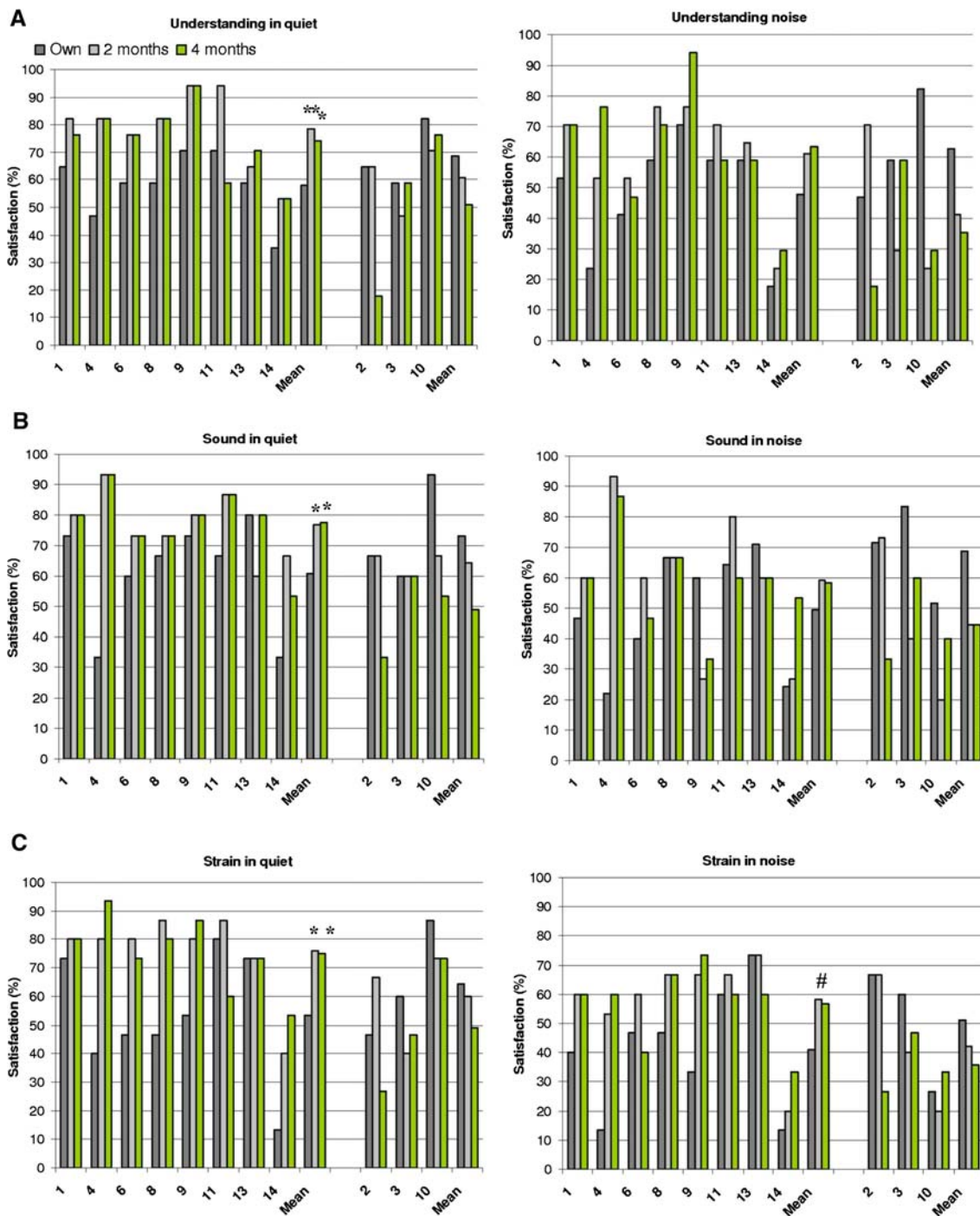


Fig. 3 Experimental device satisfaction. Mean satisfaction levels in percent obtained by the 11 hearing-impaired subjects, comparing **a** understanding, **b** sound intensity and **c** strain of their own hearing instruments with the experimental devices equipped with the non-

linear frequency compression algorithm. Scores averaged across satisfied subjects (8) and not satisfied subjects (3) are shown. Statistical significance is shown by asterisk symbols * $p < 0.05$, ** $p < 0.01$, # $p = 0.08$

showed a greater benefit for the HI wearers either in quiet or in noisy environments (Fig. 4).

Furthermore, also the occurrence of dead regions may interfere with the intention of enhanced speech intelligibility through the non-linear frequency compression

algorithm. Thus, while an audiogram may help explaining much of the auditory behaviour of a person, it does not explain it all. It seemed that patients with more severe hearing loss in high frequencies benefited most from the new algorithm, although, some fricatives have been

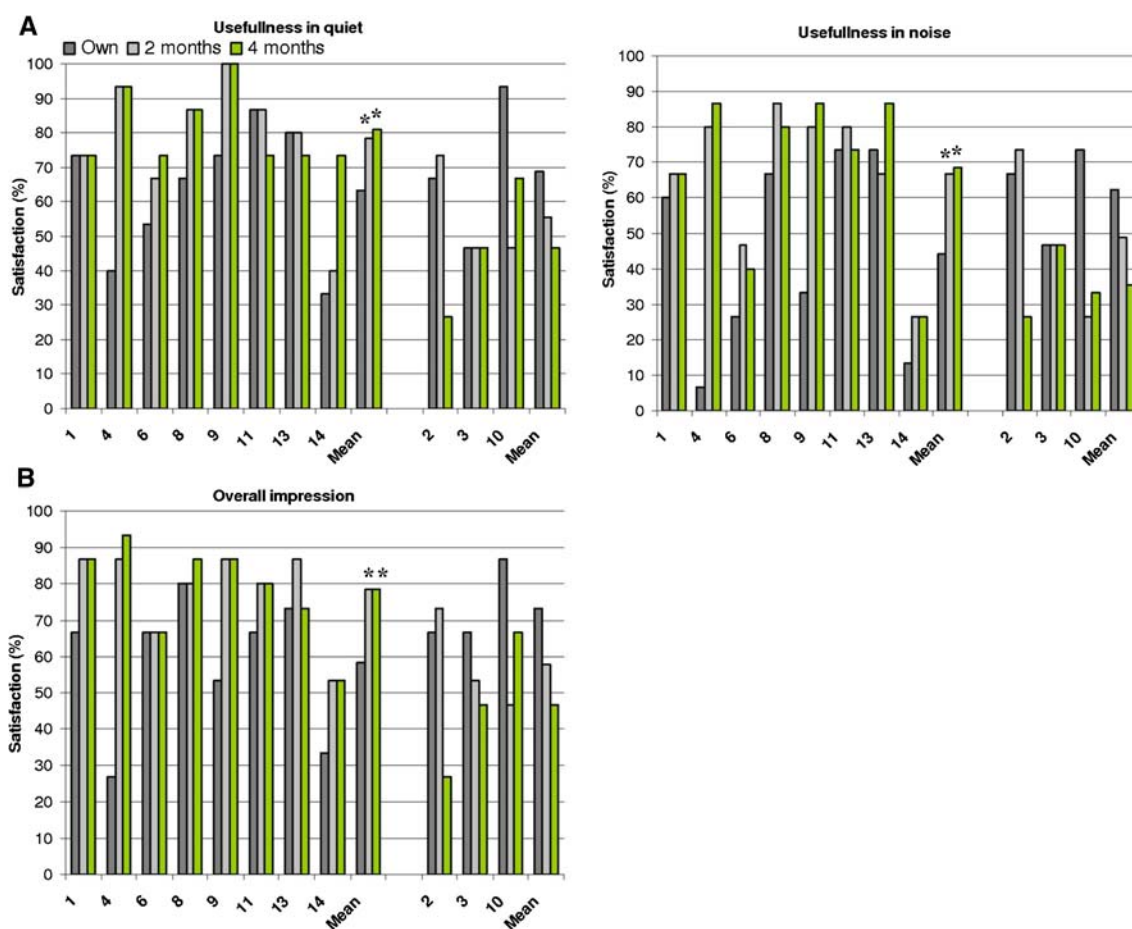


Fig. 4 Overall impression of experimental devices. Mean satisfaction levels in percent obtained by the 11 hearing-impaired subjects, comparing usefulness in quiet and noise (a) as well as both, the

overall impression for each patient (b) and shown as medians over test duration. Statistical significance is shown by asterisk symbols $*p < 0.05$, $**p < 0.01$

reported to sound unnatural. People with bilaterally symmetrical hearing losses may have quite different auditory experiences compared to people with bilaterally asymmetrical hearing losses. Furthermore, hearing losses higher than 70 dB may produce qualitatively different effects compared to losses lower than these, based on the fact that more severe hearing losses usually involve different structures within the cochlea. Additionally, many hearing impaired people have a reduced dynamic range. The compression of selected high-frequency signals into a narrower frequency range, where the listener has better residual hearing, could have enabled more effective use of the additional audible speech information, although frequency compression may introduce artefacts in intelligibility and therefore may sound unnatural. Thus, these are encouraging results for those hearing impairments affecting high frequencies.

Although we conducted the trial without additional features as beamformer or noise canceller, 7 out of 11 subjects reached a better SRT in the OLSA and 8 out of 11 subjects rated the experimental device very positively. We

conclude that the non-linear frequency compression algorithm is a valuable option for hearing impaired patients, especially for those with marked high-frequency hearing loss.

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References

- Baer T, Moore BC, Kluk K (2002) Effects of low pass filtering on the intelligibility of speech in noise for people with and without dead regions at high frequencies. *J Acoust Soc Am* 112:1133–1144
- Bagatto M, Scollie S, Glista D, Pasa V, Seewald R (2008) Case study outcomes of hearing impaired listeners using nonlinear frequency compression technology. *Audiology (Online)*

3. Byrne D, Dillon H, Tran K et al (1994) An international comparison of long-term average speech spectra. *J Acoust Soc Am* 96:2108–2120
4. Ching TY, Dillon H, Byrne D (1998) Speech recognition of hearing impaired listeners: predictions from audibility and the limited role of high-frequency amplification. *J Acoust Soc Am* 103:1128–1140
5. Hogan CA, Turner CW (1998) High-frequency audibility: benefits for hearing impaired listeners. *J Acoust Soc Am* 104:432–441
6. Johansson B (1961) A new coding amplifier system for the severely hard of hearing. In: *Proceedings of the 3rd international congress on acoustics, vol 2. Stuttgart, 1959*, pp 655–657
7. Ling D (1968) Three experiments on frequency transposition. *Am Ann Deaf* 113:283–294
8. McDermott HJ, Dean MR, Dillon H (1999) Control of hearing-aid saturated sound pressure level by frequency-shaped output compression limiting. *Scand Audiol* 28(1):27–38
9. McDermott HJ, Knight MR (2001) Preliminary results with the AVR Impact frequency-transposing hearing aid. *J Am Acad Audiol* 12(3):121–127
10. Moore BC, Glasberg BR (1997) A model of loudness speech perception applied to cochlear hearing loss. *Aud Neurosci* 3:289–311
11. Moore BC (2001) Dead regions in the cochlea: diagnosis, perceptual consequences and implications for the fitting of hearing aids. *Trends Amplif* 5:1–34
12. Neary T (1989) Static, dynamic and rational properties in vowel perception. *J Acoust Soc Am* 85:2088–2113
13. Pittman AL, Stelmachowicz PG, Lewis DE, Hoover BM (2003) Spectral characteristics of speech at the ear: implications for amplification in children. *J Speech Lang Hear Res* 46:649–657
14. Simpson A, Hersbach AA, McDermott HJ (2005) Improvements in speech perception with an experimental nonlinear frequency compression hearing device. *Int J Audiol* 44(5):281–292
15. Simpson A, Hersbach AA, McDermott HJ (2006) Frequency-compression outcomes in listeners with steeply sloping audiograms. *Int J Audiol* 45(11):619–629
16. Stelmachowicz PG, Pittmann AL, Hoover BM, Lewis D (2001) The effect of stimulus bandwidth on the perception of /s/ in normal and hearing impaired children and adults. *J Acoust Soc Am* 110:2183–2190
17. Stelmachowicz PG, Pittmann AL, Hoover BM, Lewis DE, Moeller MP (2004) The importance of high-frequency audibility in the speech and language development of children with hearing loss. *Arch Otolaryngol Head Neck Surg* 130:556–562
18. Turner CW, Hurtig RR (1999) Proportional frequency-compression of speech for listeners with sensorineural hearing loss. *J Acoust Soc Am* 106:877–886
19. Velmans M, Marcuson M (1983) The acceptability of spectrum-preserving and spectrum-destroying transposition to severely hearing-impaired listeners. *Br J Audiol* 17:17–26
20. Vickers DA, Baer T, Moore BC (2001) Effects of low pass filtering on speech intelligibility for listeners with dead regions at high frequencies. *Br J Audiol* 35:148–149
21. Wagener K, Brand T, Kollmeier B (1999) Entwicklung und Evaluation eines Satztestes für die deutsche Sprache Teil III: Evaluation des Oldenbruger Satztestes. *Zeitschrift für Audiologie* 38:86–95