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Harmonic Frequency Lowering: Effects on the Perception of Music Detail and Sound Quality

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Abstract

A novel algorithm for frequency lowering in music was developed and experimentally tested in hearing-impaired listeners. Harmonic frequency lowering (HFL) combines frequency transposition and frequency compression to preserve the harmonic content of music stimuli. Listeners were asked to make judgments regarding detail and sound quality in music stimuli. Stimuli were presented under different signal processing conditions: original, low-pass filtered, HFL, and nonlinear frequency compressed. Results showed that participants reported perceiving the most detail in the HFL condition. In addition, there was no difference in sound quality across conditions.

Keywords

harmonic, frequency lowering, frequency compression, frequency transposition, music perception, hearing loss

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Introduction

Frequency lowering is one strategy to increase the audibility of acoustic signals for the hearing-impaired listener. Higher frequencies that are inaudible for the hearing-impaired listener are mapped toward lower frequencies. Frequency lowering can be achieved by frequency transposition (FT) and frequency compression (FC) (Kuk, Keenan, Korhonen, & Lau, 2009). In frequency transposition, the high-frequency components of the spectrum are shifted lower and mixed with the original signal. In frequency compression, the high-frequency portion of the spectrum is compressed to fit into a narrower target bandwidth, and there is no spectral superimposition of the original and the compressed signal. The mapping curve can be linear or nonlinear. Linear frequency compression (LFC) maps all input and output frequencies according to the equation $f_{out} = constant * f_{in}$ (Equation 1). In nonlinear frequency compression (NFC), the mapping between the input and output frequencies can be described by $f_{out} = f_c^{1-1/constant} * f_{in}^{1/constant}$ (Equation 2) for frequencies above a cut-off f_c. Typically, the low-frequency components remain unmodified in NFC. Figure 1 shows examples of the input–output functions for FT, LFC, and NFC strategies.

Frequency-lowering technology currently exists in the hearing aids of many hearing-aid manufacturers (Galster, Valentine, Dundas, & Fitz, 2011; Kuk et al., 2006; Kuriger & Lesimple, 2012; McDermott, Baldwin, & Nyfeller, 2010; McDermott & Knight, 2001; Serman, Hannemann, & Kornagel, 2013; Stender & Groth, 2014). The hearing aids feature FT, LFC, and NFC strategies, and the parameterization can be individually adjusted to the hearing-impaired listener. Depending on the manufacturer, the activity of the lowering schemes is either fixed or adapts to the input signal so that frequency-lowering is only active when relevant acoustic features have been identified.

The primary purpose of frequency lowering in hearing aids is to increase speech intelligibility. Frequency lowering also has a positive side-effect on feedback cancelling as a result of decorrelating the input and the output signal (Joson, Asano, Suzuki, & Sone, 1993). Consequently, frequency lowering has become an integral feature of hearing aid signal processing. This feature, however, has not been adapted or optimized for music.

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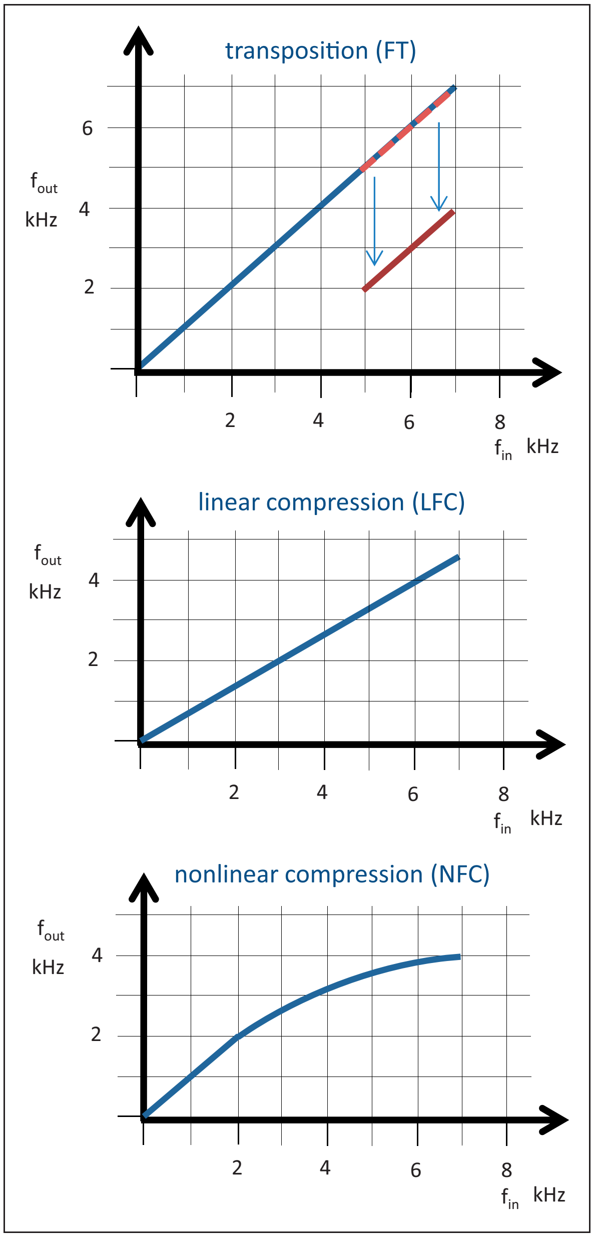

Figure 1. Examples of the input–output mapping functions for the different frequency lowering schemes frequency transposition (FT), linear frequency compression (LFC), and nonlinear frequency compression (NFC). (FT: cut-off frequency 5 kHz, peak frequency: 6 kHz, frequency shift 3 kHz; LFC: compression ratio 3:2; NFC: cut-off frequency 2 kHz, compression ratio 1.7).

Benefit of Frequency Lowering on Speech Intelligibility

The vast majority of studies shows that NFC benefits speech intelligibility in hearing-impaired listeners, especially, in the perception of fricatives and affricatives (Alexander, 2012; Alnahwi & AlQudehy, 2015; Bohnert, Nyffeler, & Keilmann, 2010; Ellis, 2012; Glista et al., 2009; Glista, Scollie, & Sulkers, 2012; Kopun et al., 2012; Marchesin & Iorio, 2015; McCreery et al., 2013, 2014; Nyffeler, 2008; Simpson, Hersbach, & McDermott, 2005, 2006; Souza et al., 2013; Stender & Groth, 2014; Wolfe et al., 2010, 2011).

Evidence for effects of LFC on speech intelligibility is limited. Those studies that have been completed have small sample sizes and hard-to-interpret findings. Parent, Chmiel, and Jerger (1998) measured a significant improvement for speech understanding in two out of four participants. McDermott, Dorkos, Dean, and Ching (1999) obtained evidence for minimal improvement with LFC but noted that the low-frequency electro-acoustic characteristics may have been responsible for these improvements rather than frequency lowering. In a later study, McDermott and Knight (2001) did not find differences in the recognition of monosyllabic words and consonants in the LFC condition but found significant decreases in understanding of sentences in noise.

Studies on FRED (Rees & Velmans, 1993; Velmans & Marcuson, 1983), an early FT implementation, revealed a clear benefit for discrimination of consonants. Subsequent studies have corroborated benefits of FT for speech intelligibility (Auriemmo et al., 2009; Gou, Smith, Valero, & Rubio, 2011; Kuk et al., 2009; Robinson, Baer, & Moore, 2007; Smith, Dann, & Brown, 2009). However, other studies have found no effect on speech intelligibility (Robinson, Stainsby, Baer, & Moore, 2009) or even a detrimental effect (Alexander, Kopun, & Stelmachowicz, 2014).

Differences in outcomes with FL may not only be attributed to the FL strategy but also to the sample size and to the participants' degree of hearing loss.

Effect of Frequency Lowering on Sound Quality of Speech and Music

Regarding the effects of frequency lowering on sound quality of speech, the clinical evidence is scarce and limited to studies involving NFC. Souza et al. (2013) measured a decrease in speech quality for the NFC condition. Parsa, Scollie, Glista, and Seelisch (2013) found that hearing-impaired listeners were less sensitive than normal-hearing listeners to quality differences between conventional amplification and different NFC parameterizations. In general, sound quality was lower in NFC, and the cut-off parameter effected quality judgments more than the compression ratio. Brennan et al. (2014) revealed that preference of NFC over conventional amplification was dependent on bandwidth. Participants preferred NFC over conventional amplification if the bandwidth of the conventionally amplified signal was limited to the bandwidth of the NFC signal (i.e., around 5 kHz). However, when the bandwidth of the conventionally amplified signal was not limited (i.e., 11 kHz), no preference for NFC was observed.

Research on the effects of frequency lowering on music is also lacking. Uys, Pottas, Vinck, and Van Dijk (2012) found that NFC led to improvements in reverberance, tinniness, and overall fidelity. Parsa et al. (2013) found that while normal-hearing individuals had a preference for conventional amplification over NFC with music signals, the same preference was non-existent in hearing-impaired listeners. Brennan et al. (2014) report that the degree of high-frequency loss affects preference ratings. Participants with greater high-frequency hearing loss are more likely to prefer NFC, while participants with less high-frequency hearing loss are more likely to prefer non-compressed versions with full bandwidth.

All in all, the state-of-the-art frequency-lowering technologies show a general benefit for speech intelligibility but not necessarily sound quality of speech or music.

FT and NFC represent threats to the sound quality of the music signal as they can compromise the integrity of the harmonic structure. The transposed or compressed components of the lowered signal are almost never in harmony with the original signal or low-frequency content, respectively. Figure 2 shows the spectrum of a consonant tone dyad of two complex tones with fundamental frequencies at $f_{01} = 800\,\text{Hz}$ and $f_{02} = 2000\,\text{Hz}$ (ratio 2:5) and harmonics until 8 kHz in an original version, processed with NFC, and processed with FT. In the example, the cut-off frequency for the NFC condition was set to 2 kHz; the frequency shift for the FT condition was determined by half the peak frequency $6\,\text{kHz} \div 2 = 3\,\text{kHz}$ with a corresponding source region between 4 and 8 kHz. In the NFC condition, all harmonics above 2 kHz are inharmonically distorted. Also in the FT condition, the transposition creates inharmonic components to the complex tone dyad at 1, 1.8, 2.6, 3, 3.4, and 4.2 kHz.

The frequency mapping function of LFC preserves the harmonic structure. However, as there is no cut-off frequency, LFC is also active in mid and lower frequency regions that are less likely to be affected by hearing loss or for which audibility could easily be restored through conventional amplification.

Pitch perception is manipulated by LFC. A compression ratio of 1.5:1, for example, would lower the pitch by a fifth. FT and NFC can also affect pitch perception. If components of a harmonic complex are mistuned, they give rise to a shift in pitch of the whole complex (Meddis & O'Mard, 1997; Moore, Glasberg, & Peters, 1985). It is widely agreed that the lower harmonics contribute most to this effect (Moore et al., 1985; Moore & Gockel, 2011; Plomp, 1964, 1967). Dai (2000) suggested that the most dominant harmonics are in the frequency region of 600 Hz. The manipulated frequency regions of FT and NFC are usually higher and, therefore, do not dominate the pitch perception. Nevertheless, they can still have an effect. Moore et al., 1985) have shown that a mistuning

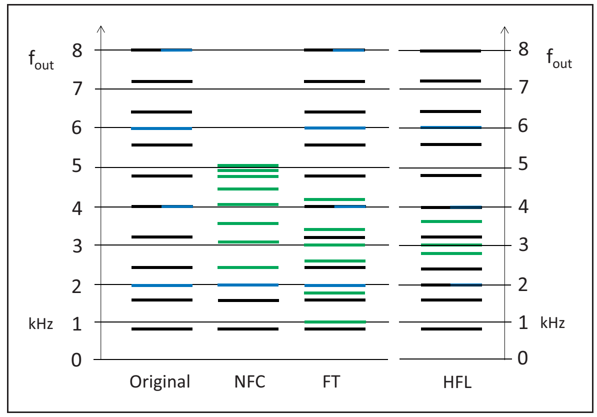

Figure 2. (a) Spectrum of a tone dyad of two complex tones with fundamental frequencies at 800 Hz (black) and 2000 Hz (blue). The cut-off frequency for the nonlinear frequency compression (NFC) condition was set to 2 kHz and the frequency shift for the frequency transposition (FT) condition was determined at 3 kHz, half the peak frequency at 6 kHz. New components to the original version after frequency lowering are marked in green.
(b) Spectrum of a tone dyad of two complex tones with fundamental frequencies at 800 Hz (black) and 2000 Hz (blue). The cut-off frequency for harmonic frequency lowering (HFL) was set at 4 kHz. New components to the original version after harmonic frequency lowering are marked in green.

of the lowest six harmonics of a complex tone with a fundamental frequency of 400 Hz has a noticeable effect on pitch perception. The fourth, fifth, and sixth harmonic in this example reach frequencies from 1600 to 2400 Hz which are well within the target region of commercial NFC and FT implementations.

In sum, FT, NFC, and LFC may not be optimal for preserving sound quality in music. The purpose of this study was to test a frequency-lowering algorithm for music that may address audibility without compromising sound quality. Testing of the algorithm was achieved by asking listeners to judge the perceived detail and quality of music presented under original, low-pass filtered, HFC, and NFC conditions.

Description of Harmonic Frequency-Lowering Algorithm

The harmonic frequency-lowering (HFL) algorithm was developed for music and combines frequency compression and frequency transposition to preserve pitch chroma and harmonic structure in music. The algorithm contains three core elements:

1. A cut-off frequency f_c separates the low-frequency content from the high-frequency content.
2. The high-frequency content is lowered by an octave (i.e., compressed by a linear factor of 2).

3. The compressed frequency content is weighted and then mixed with the original signal.

In general, a harmonic complex tone with a fundamental frequency Fo evokes a pitch perception which corresponds to Fo even if there is no energy present at Fo (Plack & Oxenham, 2005; Seebeck, 1841). Rather than organizing pitch on a one-dimensional scale from low to high, it is commonly described as a two-dimensional construct inclusive of pitch chroma (class) and pitch height (Bachem, 1937, 1950; Deutsch, Dooley, & Henthorn, 2008; Drobisch, 1852; Meyer, 1904; Révész, 1913; Stumpf, 1890). Pitch chroma refers to the position of the pitch within the octave and pitch height refers to the octave in which it is placed.

The octave is the most consonant interval (Schellenberg & Trehub, 1994), and many listeners fail to recognize octave transpositions of isolated tones (Cross & Deliège, 2004). Correspondingly, the perception of pitch height can be ambiguous depending on the context (Shepard, 1964).

A linear compression factor of 2 lowers the high frequency components by an octave. The lowered components and the original source share the same pitch chroma. The superposition of both signals in HFL, therefore, preserves the perception of pitch chroma.

Harmonic frequency lowering protects the harmonic structure and reduces a potentially negative effect of frequency lowering on tonal consonance. An interference of just-noncoinciding harmonics gives rise to the perception of beats or roughness (Helmholtz & Ellis, 2009; Vos, 1982). For pairs of sinusoids, the beating interactions are most prominent for frequency differences around 3 to 4 Hz (Ebel, 1952; Riesz, 1928; Terhardt, 1974; Zwicker, 1952).

The linear compression ratio 2:1 results in an alignment of original and lowered harmonics. The lowered even harmonics coincide with the harmonics of the original signal. The odd harmonics are mapped in the middle between two original harmonics. The distance of two adjacent harmonics in the overlapping region of the sum signal is, therefore, half the fundamental frequency Fo. These frequencies contribute to the perception of a residual or virtual pitch that is one octave lower (Schouten, 1938; Schouten, Ritsma, & Cardozo, 1962) rather than to tonal dissonance. Figure 2(b) shows the spectrum of a tone dyad as described in Figure 2(a) when processed with HFL. Compared to the original, new frequency components are created at 2.8, 3, and 3.6 kHz. This HFL tone complex can also be regarded as the original complex tone dyad with residual fundamentals at 400 Hz and 1 kHz (ratio 2:5), which share the same chroma as the original dyad and, therefore, blend well.

The linear 2:1 ratio also results in a more aggressive lowering of high-frequency content without adding distortion. An 8 kHz sinusoidal tone is lowered by 4 kHz, which is a more substantial lowering than that which is achieved in standard fittings of commercially available hearing aids. This advantage applies to all frequencies in the lowered bandwidth. Participants with sloping hearing loss or dead regions might especially benefit from this attribute. A stronger shift to lower frequencies makes it easier to restore audibility with hearing aids and helps to circumvent dead regions which are more prevalent in the higher frequencies (Pepler, Munro, Lewis, & Kluk, 2014).

Materials and Method

Participants

Nineteen hearing-impaired listeners (ages 55–80 years, $M = 71$) were recruited from the internal database of Phonak AG headquarters, Stäfa, Switzerland. Only participants with high-frequency hearing loss who had not yet experienced frequency-lowering signal processing were included. All audiometric data were assessed within 1 month of the first test date. Table 1 contains air conduction thresholds, gender, age, hearing aid, hearing aid experience, music experience, and the individual parameters used for the NFC algorithm (cut-off frequency and compression ratio, c.f. Stimuli section) for all participants. Music experience was determined according to Kirchberger and Russo (2015).

Stimuli

There were four music segments (S1–S4) selected as source material for test stimuli. All segments contained substantial high-frequency content and spanned a range of genres. The first was a 12.8-s segment from the pop song "Hey Jude" by the Beatles. It included piano, vocals, rhythm guitar, bass guitar, and a tambourine. The second was a 10.5-s segment from the jazz song "The Golden Striker" by Ron Carter. It included piano, double bass, drums (hi-hat) and vibraphone. The third was a 9.6-s segment from the latin song "Mas que nada" by Sergio Mendes featuring Black Eyed Peas. It included vocals, piano, bass, and percussion (cymbals, woodblock, claps). The fourth was a 10.5-s segment from the dance song "Touch" by Daft Punk. It included strings, bass, synthesizer, and drums (bass, snare, cymbals).

All songs were retrieved as stereo files with 20,480 Hz sampling rate and 16-bit resolution. Segments were selected in a manner that preserved musical phrasing (i.e., did not span phrase boundaries). Stimuli were played back via two loudspeakers at 1.5-m distance forming a stereo triangle with the participant.

For the main experiment, five versions of each segment were individually prepared: Original, NFC, HFL with an individual cut-off frequency (HFLi), HFL with a

Table 1. Characteristics of the Test Participants and the Individual Parameters for the Nonlinear Frequency Compression Algorithm: Audiometric Data (dB HL), Age (yrs), Hearing Aid Experience/HAE (yrs), and Music Experience/ME (Scale min: −3, Scale max: 4), Cut-off Frequency/Fc, and Compression Ratio/CR for the NFC (Nonlinear Frequency Compression) Condition.

	Left ear, frequency (kHz)								Right ear, frequency (kHz)													NFC	
	0.13	0.25	0.5	1	2	4	6	8	0.13	0.25	0.5	1	2	4	6	8	Sex	Age	HA	HAE	ME	Fc	CR
P1	30	30	35	60	60	70	115	105	30	35	35	45	60	70	90	80	M	80	Oticon Acto	11	2.5	3.4	2.2
P2	20	10	5	20	65	75	85	100	25	20	10	5	40	70	90	90	F	64	Resound Azure	>10	1	3.4	2.2
P3	10	10	5	25	45	60	85	100	15	10	15	10	55	90	100	100	M	72	Oticon	7	−1.5	3.8	2.4
P4	5	10	20	55	65	70	80	75	10	10	15	30	75	70	90	80	M	74	Phonak Savia 221	12	−2	3.5	2.3
P5	40	45	45	65	70	80	90	80	35	35	40	50	60	80	80	75	M	67	Widex PA 115	>10	1.5	3.8	2.4
P6	25	40	40	75	75	100	105	105	15	20	30	35	45	65	75	85	M	73	Phonak Savia 211	8.5	−1	3.6	2.3
P7	10	20	55	70	75	85	95	90	10	10	20	50	65	95	100	100	M	72	Siemens Pure 700	6	−2.5	3	2
P8	15	15	25	50	55	75	100	95	15	15	20	25	70	85	100	105	M	70	Phonak Audeo V50	0.2	−2	3	2
P9	20	15	5	30	45	90	105	95	10	10	10	45	40	100	100	100	M	70	Widex	10	−3	3.2	2.1
P10	25	30	55	70	75	75	80	85	25	25	35	50	70	70	75	75	M	65	Resound Verso	8	0	3.5	2.2
P11	15	30	55	75	75	80	85	90	40	45	50	65	75	85	100	85	M	73	Phonak Extra 22D	16	−2.5	3.2	2.1
P12	40	50	50	65	90	95	>110	105	35	40	45	50	65	105	>110	>110	M	78	Widex CAFS	45	−2.5	2.7	1.8
P13	25	40	65	90	75	75	105	>120	30	40	45	60	90	75	90	121	M	69	Widex M4-9	50	−3	3	2
P14	20	30	35	35	50	60	70	65	30	30	35	40	40	65	85	80	M	69	Oticon Agil	9	−2.5	4.5	2.7
P15	50	55	60	80	75	75	95	105	50	50	45	45	75	75	105	110	M	70	Siemens Pure 500	12	−1.5	2.8	1.9
P16	15	15	10	55	60	65	90	95	15	10	10	15	55	65	80	95	M	76	Oticon Alta Pro	12	0	3.1	2.1
P17	40	50	55	80	85	95	100	>115	20	25	40	40	55	80	NT	85	M	71	GN Resound Live	5	0.5	3.3	2.1
P18	30	30	65	80	80	85	90	85	25	25	35	40	55	80	90	90	M	75	GN Resound Live	21	1.5	3.1	2
P19	10	5	10	45	65	80	105	85	5	10	10	15	65	80	90	75	F	55	Oticon	7	−2	3.3	2.2

Note. HAE = hearing aid experience; ME = music experience; Fc = cut-off frequency; CR = compression ratio; NFC = nonlinear frequency compression; NT indicates a hearing threshold that was not tested.

default cut-off frequency (HFLo), and a low-pass filtered version (LP). All files were processed offline to eliminate potential delays.

The compression parameters of NFC (i.e., cut-off frequency and compression ratio, Table 1) were individually fitted according to the recommendation of the Target™ fitting software.

In the HLFi condition, the cut-off frequency was defined as twice the cut-off frequency from the NFC setting. As a result of this definition, the bandwidth of the lower unmodified part of the signal in the HFLi condition equaled the bandwidth of the lower unmodified part of the signal in the NFC condition. Furthermore, the HFLi signal was low-pass filtered to match the total bandwidth of the NFC signal. As there was a spectral overlap of the original signal and the frequency-compressed components, the frequency-compressed component was amplified to be adjusted in level. The gain for the level of the frequency compressed component in the HFLi signal was determined in a pretest (c.f. Procedures section).

The only difference between HFLi and HFLo is that for HFLo, the cut-off frequency was fixed at 4 kHz rather than being determined according to the hearing loss of the individual participants. Octave lowering in both HLFo and HLFi was implemented using the pitch-shift plugin SoundShifter from Waves (2013).

The LP condition was generated by reducing the bandwidth of the original signal to the bandwidth of the frequency-lowered conditions (NFC and HFL).

Figure 3 depicts examples of input–output functions for all five conditions. Figure 4 shows an example of how the spectrum of the HFLo condition differs from the spectrum in the LP condition due to the addition of the lowered content.

Procedures

Participants were invited to two separate sessions. In the first session, the pretest was conducted along with the main tests for music detail and sound quality. The participants' existing hearing aids were also tested to verify the absence of frequency lowering. In the second session, both main tests were repeated and participants filled out the music questionnaire as in Kirchberger and Russo (2015).

Pretest. The pretest served as a fitting procedure for the HFL conditions. The lowered portion of the signal and the original signal had overlapping frequency content. Using a virtual slider, participants were asked to adjust the signal with regard to two objectives. In the first instance, they were asked to adjust the slider to the

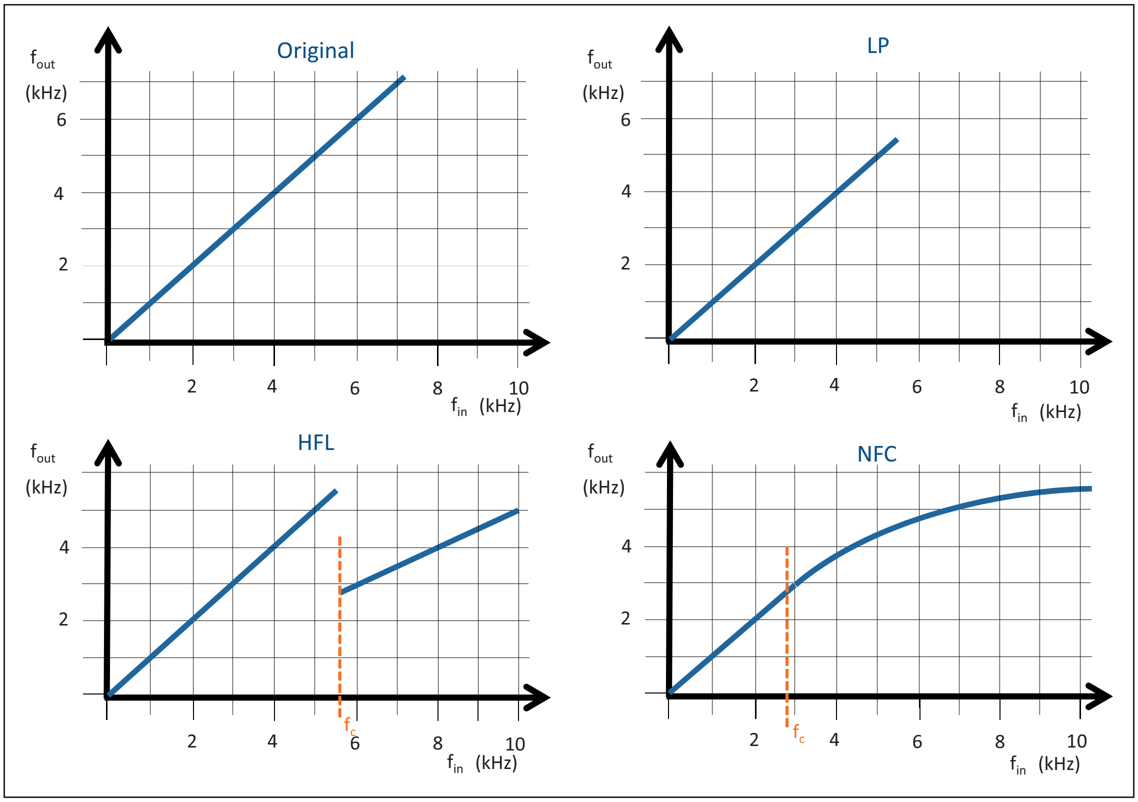

Figure 3. Schematic of the different input–output functions that were evaluated in the main test.

lowest position with which they could detect a difference (i.e., detection threshold). In the second instance, they were asked to adjust the slider to the position that was preferred. In both instances, participants adjusted the amount of gain that was applied to the lowered portion of the signal. However, participants were not informed with regard to how exactly the signal was being modified.

If the gain corresponding to the preferred position was higher than the gain corresponding to the detection threshold, the mean of the two gains was applied to the compressed signal in the HFL conditions. If the gain corresponding to the preferred position was lower than the gain corresponding to the detection threshold, the gain at the detection threshold was applied to the compressed signal in the HFL conditions. This last measure was necessary to ensure that there would always be a perceptual difference between HFL and LP signals. All versions of each segment were presented at an output level of 65 dB SPL.

Main test. The setup of the main tests was a multistimulus test method similar to a MUSHRA setup as described by the Recommendation ITU-R.1534 (2001).

In each trial, participants had to compare and rate five stimuli versions on a scale from 0 to 100. The stimuli versions were original, NFC, HFLo, HFLi, and LP. A separate trial was carried out for each music segment. An example screen for one trial is displayed in Figure 5. The different conditions were randomly assigned to different buttons (A–E). Participants were asked to make judgments along two dimensions: music detail and sound quality. Music detail was further paraphrased to the participants as additional acoustic content that enriches the music such as instruments, melody parts, or rhythmic elements. It was made clear that artifacts or other audible effects that do not belong to music were not to be considered in the evaluation of music detail. The intention with the detail dimension was to measure how much effect harmonic frequency lowering had on the audibility of music content. The intention with sound quality was to find out whether the perceivable lowered signal components were considered positive or detrimental from an aesthetic perspective. Participants were instructed to focus on the relative differences between the conditions within one trial rather than trying to make absolute ratings across trials. The scales used for the rating ranged from "low" to "high" for detail and "poor" to "good" for sound quality.

First, all trials for music detail were carried out. Then there was a pause. After the pause, all trials for sound quality were carried out. Participants conducted the test twice on two separate occasions, with one trial for every segment and question resulting in a total of $2 \times 4 \times 2 = 16$ trials.

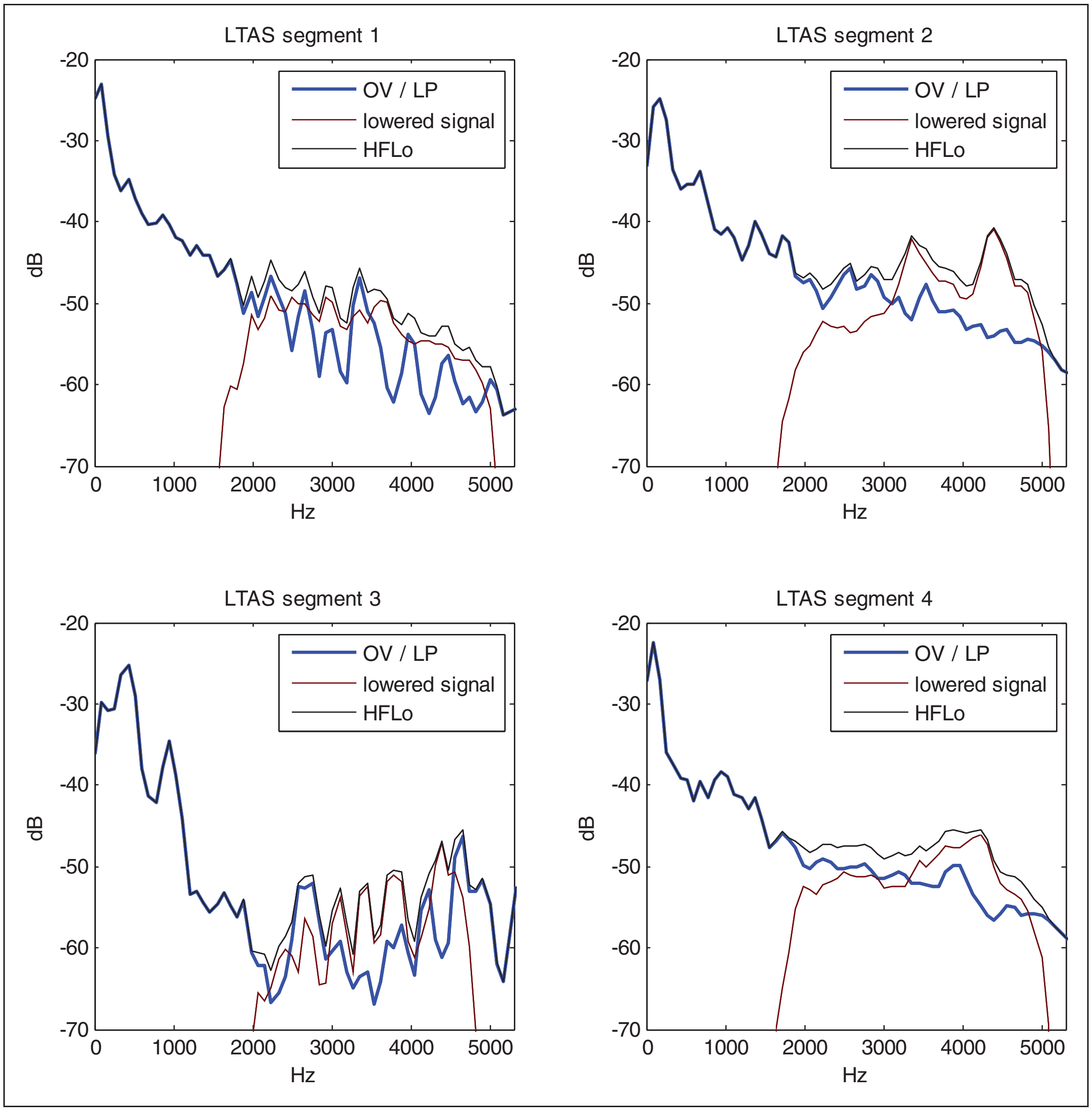

Figure 4. Long-term average spectra of the four music segments in the OV/LP condition, the HFLo condition and the spectra of the lowered signal for a gain weight of 0 dB.

The stimuli were looped endlessly within their channel A, B, C, D, or E (c.f. Figure 5). As the original stimuli were selected to preserve musical phrasing, the transitions from the end to the beginning of each loop were unnoticeable. Participants were freely able to switch between stimuli or channels respectively at any given time. A 5-ms cross-fade was applied while channel switching in order to avoid switching artifacts such as cracks.

Results

Pretest

The gain weights were specified as the energy difference between the compressed signal and the coinciding original signal in the spectral region within which the two signals overlap. Table 2 depicts the gain weights for the four music stimuli in the conditions HFLi and HFLo. Positive gain weights imply that the compressed signal was higher in level than the original signal. A repeated-measures ANOVA was performed with measurement (threshold, preference), condition (HFLo, HFLi), and music segment (S1-S4) as within-subjects factors. As proposed by Girden (1992), in cases where sphericity was violated, Greenhouse-Geisser corrections were used if the epsilon test statistic was lower than 0.75; otherwise, the Huynh-Feldt corrections were applied. There were no main effects of measurement or segment, but a significant main effect of condition, $F(1,\ 18) = 10.07$, $p = .005$. The gain weights for the

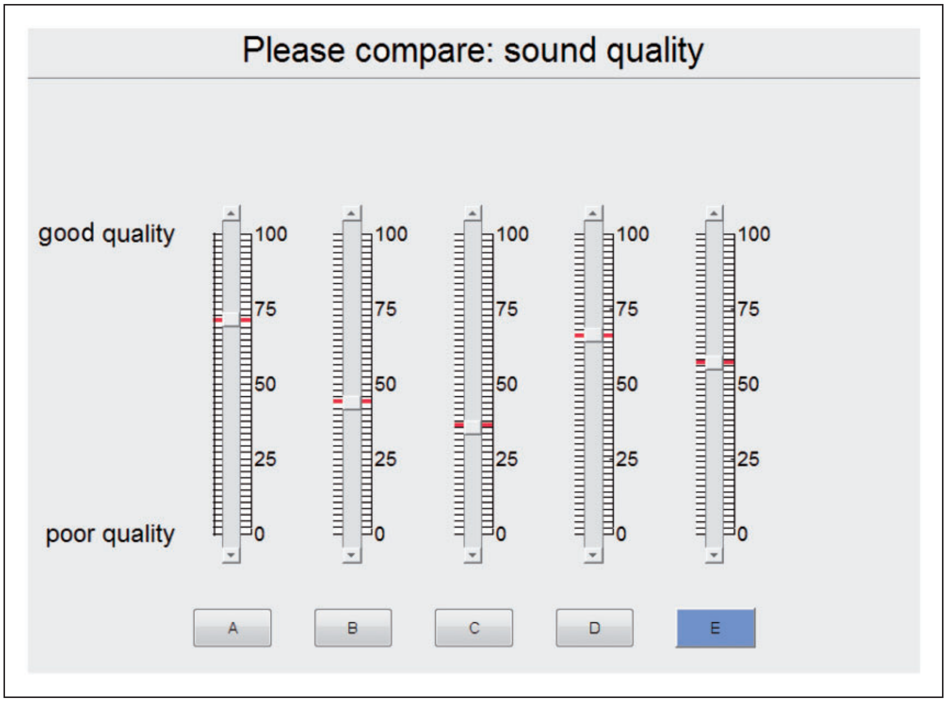

Figure 5. Example screen of the main test.

HFLi condition (mean: 4.42 dB) were significantly higher than the gain weights for the HFLo condition (mean: 1.74 dB).

Main Test

For music detail and music quality, a repeated-measures ANOVA was performed with session (test, retest), condition (Orig., NFC, HFLi, HFLo, LP), and segment (S1–S4) as the within-subject factors.

For music detail, there was no main effect of session or segment but a significant main effect of condition, $F(2.1,\ 38.2) = 44.49$, $p < .001$. The mean values and standard errors of the difference scores in all conditions are displayed in Figure 6. Participants perceived the most detail in the HFL conditions (HFLi: 68.6, HFLo: 72.1), followed by NFC (50.0), Original (47.8), and LP (41.7). Bonferroni corrected pair-wise comparisons revealed significant differences between all conditions apart from Original versus NFC, Original versus LP, and HFLi versus HFLo. The corresponding statistics are displayed in Table 3.

With regard to music quality, the effects of session and segment were not significant.

Although the pattern of quality ratings across conditions were more or less consistent with the pattern obtained for detail (HFLo: 56.6, HFLi: 55.2, Original: 52.2, NFC: 51.8, and LP: 50.0), the effect of condition was not significant, $F(1.6, 28.8) = 1.27$, $p = .290$.

Discussion

HFL conditions were found to be superior to all other conditions with respect to music detail. In addition, the HFL conditions did not have a detrimental effect on music quality. One interpretation of this finding is that high-frequency elements that were not audible in the original or low-passed filtered version of each segment became audible in the HFL conditions. The advantage of HFL over NFC for music detail may be explained by two factors: First, the frequency lowering in HFL is more aggressive than in NFC. Second, the maintenance of naturally occurring harmonic ratios in the HFL condition might preserve the naturalness of the signals better than NFC and, therefore, facilitate the detection of instruments, melody, harmony, rhythm, and other music details. Due to the preservation of the harmonic structure, the lowered content tends to be considered musical. Although it would be possible to implement more aggressive NFC to improve the audibility of sounds with substantial high-frequency content, this would inevitably introduce even more harmonic distortion.

One criticism of the above interpretation of the music detail findings might be that the benefit was owed to the amount of gain applied to the frequency lowered signal. If high gains are applied, the signal energy in the target region ends up being substantially higher in the HFL conditions than in the other conditions. The increase in

Table 2. Gain Weights in dB at the Point of Detection and Preference for HFLi and HFLo.

	Detection								Preference							
	HFLi				HFLo				HFLi				HFLo			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
P1	−3	0.1	5.7	−1.7	−5.9	−1.3	−4.1	0.9	−9.2	−4	−6.4	−6	−7.6	−2.9	−8.2	−1.5
P2	−2.1	2.2	1.3	−3.5	−2.4	−2.6	−0.9	−3.5	−10	−3.4	−10	−6.1	−3.7	−6.1	−10	−10
P3	−0.6	6.4	3.2	5.1	−0.5	−0.4	1.9	−4.8	19	18	18	17	8.4	10	12	6.4
P4	−4.5	−7	−4.5	−3.4	−6.6	−4.2	−4.8	−6.6	−3	−0.2	−6.4	2.3	−4.4	−4.4	−3.2	−2.1
P5	1.4	−2.2	−0.8	2	8.2	3.1	4	5.8	12	13	9.2	11	7	8.1	10	7.6
P6	−0.6	0	−3.7	0	−2.5	−2.5	−2.5	−5	−10	−7.5	−7.5	5	−4.4	−7.5	−5	2.5
P7	3	6.1	2.8	5.9	−2.2	−1.3	6.8	1.9	3.8	−1.6	2.2	2.2	−4.4	−3.4	−2.2	−0.9
P8	2.2	2.2	1.2	0.5	2.3	1.6	0.9	6.1	0.9	6.8	−6.6	8.6	0.3	5.1	−1.6	7.1
P9	17	13	18	14	13	9	16	15	10	13	15	16	13	8.3	14	11
P10	2	8.8	−1	8	8	5	5	2	8	11	13	11	−1.9	−0.2	0.5	1.8
P11	−5.3	−4.3	1.4	−3.6	−3.5	−6.9	−0.5	−4.8	1.4	1	4	−0.3	−1	−3.2	1.7	−4.5
P12	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
P13	12	11	19	17	14	11	14	10	16	15	17	14	11	8.9	15	12
P14	9.7	12	10	9.5	−5.9	−6	−4.8	−5.3	9.5	8.9	10	10	−5.7	−5.2	−4.6	−4.3
P15	2.4	−1.1	2.2	1.5	0.8	−3.4	−1.3	0.8	1.2	−1.9	0.1	−3.7	0.1	−6	−4	2
P16	−0.4	0.5	−0.4	−1.3	−2.7	−2.4	−1.8	−2.5	−1.4	1.4	−1.3	−1.9	−2.6	−2.2	−1.7	−2.4
P17	−3	0.1	5.7	−1.7	−5.9	−1.3	−4.1	0.9	−0.1	6.3	0.1	5.6	−2	−0.2	−0.6	−1.8
P18	−6.6	−8.5	−7.6	−6.6	−8.2	−8.8	−4	−8.6	−10	−9.2	−7.5	−8.6	−10	−9.6	−6.1	−10
P19	12	18	17	13	9.7	9.5	13	8.5	19	17	21	14	14	10	15	12
MEAN	3	4	4.7	3.9	1.6	0.9	2.8	1.6	4	5.4	4.4	5.8	1.4	1	2.2	2.4

Note. HFLi: HFL with an individual cut-off frequency; HFLo: HFL with a default cut-off frequency.

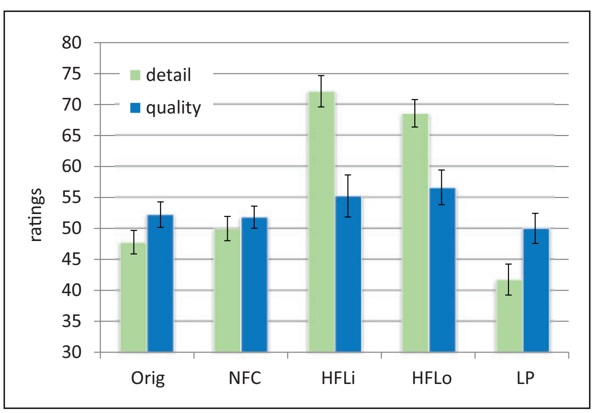

Figure 6. Mean ratings and standard errors for detail and quality in the 5 conditions under test (Orig: Original, NFC: nonlinear frequency compression, HFLi: harmonic frequency lowering with individual cut-off frequency, HFLo: harmonic frequency lowering with default cut-off frequency, LP: low pass).

energy was counterbalanced by normalizing all stimuli to the same root mean square (RMS) level before playback. Nevertheless, spectral differences between conditions might still contribute to variations in loudness and brightness. To address these potential effects from applying gain to the lowered content, a post-hoc repeated-measures ANCOVA was performed with the gain weights as covariate. This post-hoc analysis revealed that the effect of the amount of gain on the perception of detail was not significant, $F(1, 17) = 0.259$, $p = .617$. In addition, a post-hoc repeated-measures ANOVA was performed on a subgroup of participants who assigned average gain weights of less than 0 dB to the frequency lowered signal. This post-hoc analysis yielded the same result as the original analysis: Both HFL conditions were superior to all other conditions in music detail, $F(1.7, 10) = 13.13$, $p = .002$, without a detrimental effect on music quality, $F(1.2, 7.5) = 0.72$, $p = .453$. To further assess a potential bias of the increase in high-frequency energy on the results on detail, a follow-up study could be conducted in which the high-frequency energy of the other conditions is elevated to the same level. Likewise, the RMS level of the high-frequency content in the HFL conditions could be adjusted to the RMS level of the high-frequency content in the original version.

With regard to music quality, participants did not have a clear preference for either condition. None of

Table 3. Statistics of Pair-Wise ANOVAs for Music Detail Between all Five Conditions.

	NFC	HFLi	HFLo	LP
Orig	F (1,18) = 2.71, p = .117	F (1,18) = 81.87, p < .001	F (1,18) = 50.79, p < .001	F (1,18) = 6.50, p = .020
NFC		F (1,18) = 52.60, p < .001	F (1,18) = 40.42, p < .001	F (1,18) = 10.60, p = .004
HFLi			F (1,18) = 3.20, p = .090	F (1,18) = 59.49, p < .001
HFLo				F (1,18) = 49.30, p < .001

Note. The Bonferroni-corrected significance level is $p = .005$. HFLi: HFL with an individual cut-off frequency; HFLo: HFL with a default cut-off frequency.

the participants had experienced frequency lowering prior to the experiment. Acclimatization to relearn the new mapping in the auditory periphery might be necessary in order to appreciate an improvement in the sound quality of music. Several studies demonstrate a learning effect of frequency lowering for speech intelligibility (Glista et al., 2012; Kuk & Keenan, 2010; Wolfe et al., 2010, 2011) and the same might apply for sound quality of music and the perception of music detail.

As we instructed our listeners to respond to detail holistically, we do not know which attributes contributed to the perception of detail. Based on a pretest and random post-hoc queries, we assume that the audibility of the high-frequency instruments such as cymbals and an improvement in the perception of the melodies mainly contributed to the detail ratings. The lack of performance-based measures such as instrument detection or melody discrimination task did not allow for further analysis. As part of a more complete assessment of music detail, the adaptive music perception test (Kirchberger & Russo, 2015) could be used. The adaptive music perception test is a computer-driven test that provides discrimination thresholds across 10 low-level physical dimensions (e.g., duration, level) in the context of perceptual judgments about musical dimensions: meter, harmony, melody, and timbre.

All test segments contained substantial high-frequency content. The benefit of HFL for music stimuli without substantial high-frequency content may be reduced. Further research is needed to investigate the relevancy of lowering high-frequency content in music.

Conclusion

HFL is a novel frequency-lowering method that preserves the harmonic ratios inherent in the music signal. In this study, an overall improvement in the perception of music detail without detriment for quality was observed for two implementations of an HFL algorithm. Acceptance of the new algorithms might have been even stronger following an acclimatization period as participants had not previously experienced frequency lowering. Future research should consider how HFL can be optimally fitted and assess how its benefit may evolve with acclimatization.

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