



Review

Auditory perceptual efficacy of nonlinear frequency compression used in hearing aids: A review

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Abstract

Many patients with sensorineural hearing loss have a precipitous high-frequency loss with relatively good thresholds in the low frequencies. This present paper briefly introduces and compares the basic principles of four types of frequency lowering algorithms with emphasis on nonlinear frequency compression (NLFC). A review of the effects of the NLFC algorithm on speech and music perception and sound quality appraisal is then provided. For vowel perception, it seems that the benefits provided by NLFC are limited, which are probably related to the parameter settings of the compression. For consonant perception, several studies have shown that NLFC provides improved perception of high-frequency consonants such as /s/ and /z/. However, a few other studies have demonstrated negative results in consonant perception. In terms of sentence recognition, persistent use of NLFC might provide improved performance. Compared to the conventional processing, NLFC does not alter the speech sound quality appraisal and music perception as long as the compression setting is not too aggressive. In the subsequent section, the relevant factors with regard to NLFC settings, time-course of acclimatization, listener characteristics, and perceptual tasks are discussed. Although the literature shows mixed results on the perceptual efficacy of NLFC, this technique improved certain aspects of speech understanding in certain hearing-impaired listeners. Little research is available on speech perception outcomes in languages other than English. More clinical data are needed to verify the perceptual efficacy of NLFC in patients with precipitous high-frequency hearing loss. Such knowledge will help guide clinical rehabilitation of those patients.

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Keywords: Nonlinear frequency compression; Hearing loss; Hearing aids; Speech perception; Music perception

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1. Introduction

Hearing aids have long been used to improve the communicative ability in hearing impaired (HI) listeners. However, for some HI individuals, especially for those with a severe-to-profound hearing loss at the high-frequency regions, most currently used hearing aids cannot provide equivalent benefit as they do for those with a less severe hearing loss. One reason is the limited audibility bandwidth of the hearing device, which potentially restricts HI listeners' accessibility to high frequency cues that are crucial for the identification of some phonemes such as /s/ and /z/ with a spectral peak higher than 7 kHz (Pittman et al., 2003; Lee and Choi, 2012). In addition, high-frequency components in a speech spectrum could be inaudible due to “dead regions” in the corresponding areas of the cochlea (Pepler et al., 2014) even though they are located within the bandwidth of the hearing device and receive sufficient gain through signal processing. For those individuals with a severe-to-profound high-frequency hearing loss, simple amplification of the high-frequency components does not improve speech intelligibility but rather, in some cases, produces detrimental effects on their speech perception (Ching et al., 1998, 2001; Hogan and Turner, 1998). One potential strategy is to lower the high-frequency components, making them fall into the limited processing bandwidth of the hearing device and the physiological audible bandwidth of the impaired peripheral auditory system. This method has been technically called “frequency lowering”. In the following sections of this review, we briefly introduce the four types of frequency lowering strategies and then focus on nonlinear frequency compression (NLFC), which has been widely used in contemporary hearing aids. The efficacy of NLFC on speech perception as well as music appreciation is summarized and relevant factors associated with the perceptual outcomes are discussed.

2. Frequency lowering techniques

There are four types of commonly used frequency lowering techniques, i.e., slow playback, vocoder-based frequency lowering, frequency transposition, and frequency compression. Slow playback is the simplest way of frequency lowering. This technique is characterized by playing back sections of a speech signal at a much slower rate than the original recording

which helps “preserve frequency components between harmonic information” (Simpson, 2009). The spectrum is lowered by resampling the recorded sound using a lower sampling frequency. This method causes distortion when the signal is stretched in time and introduces some negative consequences on real-time communication.

Vocoder-based frequency lowering follows the principles of vocoder processing (see Xu, 2006; Xu and Pfingst, 2008 for a review). In principle, temporal envelopes of the speech signal from higher-frequency bands are extracted and used to modulate lower-frequency carriers. The carriers may either be pure tones or narrow-band noise. Thus, the temporal envelopes that carry important speech information in the higher frequency regions are “moved” to the lower frequency regions. Kong and Mullangi (2013) used this technique on a speech recognition test and the results showed significant benefit for the perception of fricative consonants and perception of the place-of-articulation feature for a group of six HI listeners. However, early vocoders produced poor sound quality and confusions between voiced and voiceless sounds (Simpson, 2009).

For frequency transposition, the high-frequency speech signal is shifted downwards, overlapping with a certain range of unprocessed low frequency components. This strategy is the first frequency-lowering technique applied to commercial hearing aids (Johansson, 1959). Kuk et al. (2006, 2009) described the mechanism of the frequency transposition scheme that is implemented in the Widex Inteo hearing aids. In such a scheme, the high-frequency signal above a “start frequency” is moved downwards and mixed with the original sounds (see Fig. 1, bottom). In principle, this approach provides hearing aid users audibility of previously inaudible high-frequency information. While independent, well-controlled studies with frequency transposition were limited, one recent study reported that frequency transposition failed to improve the performance of fricative and affricate perception in both normal-hearing (NH) and HI listeners (Alexander et al., 2014).

Frequency compression can be linear or nonlinear (Fig. 1 top and middle panels). Linear frequency compression lowers all frequency components by the same degree. The new frequencies can be derived from the original frequencies by multiplying a constant factor (e.g., 0.7). In this way, the internal spectral structure or the ratio among various components, as well as the relationship of formant peaks, are preserved. While the preservation of formant structure is

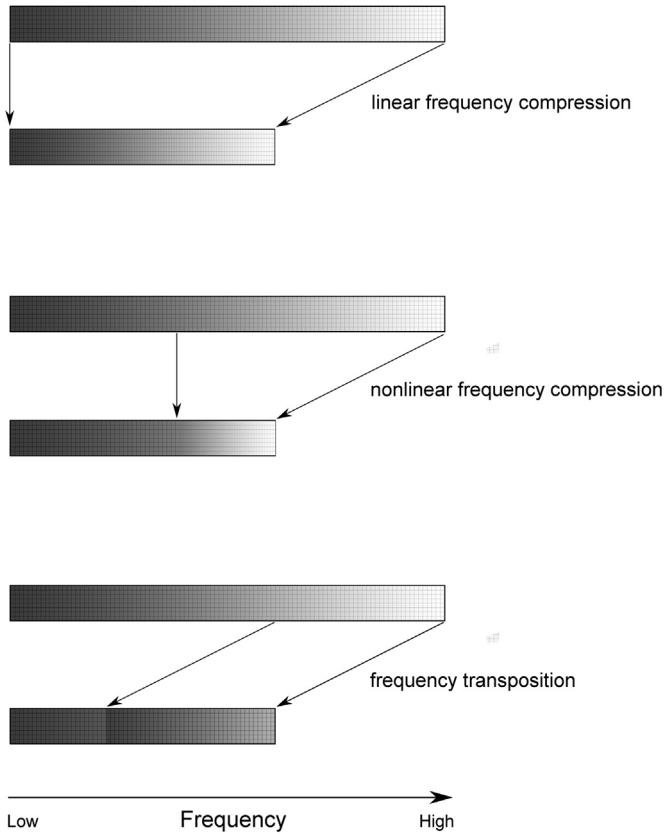


Fig. 1. The basic principles of frequency transposition (bottom), linear (top) and nonlinear frequency compression (middle).

crucial for the identification of vowels (Neary, 1989), the perceived pitch is lowered (Simpson, 2009), such that female voices may sound like male voices. In contrast, in NLFC as initially proposed by Sekimoto and Saito (1980), high-frequency components of the original speech are compressed disproportionately to a greater extent than the low-frequency components of the original speech.

Over the decades, the NLFC algorithm has progressed and been implemented in many hearing aid devices. One example of the NLFC algorithm is the SoundRecover strategy

developed and adopted by Phonak Naída hearing instruments (McDermott, 2008). In the first generation of SoundRecover (SR-1), there are two adjustable parameters, i.e., the cut-off frequency (CF) and the compression ratio (CR). Similar to the above-mentioned “start frequency”, the CF determines the start point of compression. The frequencies above the CF are compressed whereas those below the CF are not. The CR determines the strength, or degree, of the compression. A higher CR means a stronger compression. More recently, Phonak implemented a second generation of the SoundRecover algorithm called SoundRecover-2 (SR-2) which uses an adaptive algorithm instead of the static algorithm as applied in SR-1. Fig. 2 shows the comparison between these two SR algorithms. SR-2 involves a low-frequency CF and a high-frequency HaPro (harmonic protection) but the selection of CF or HaPro is conditional. The system automatically chooses HaPro as the cut-off frequency when high spectral energy (i.e., vowel sound) is detected. Otherwise, the system uses the CF as the cut-off frequency. Compared to SR-1, SR-2 maintains the vowel features and meanwhile enables a wider frequency range for compression with a lower compression ratio for fricatives. For both SR-1 and SR-2, if listeners have relatively more preserved high-frequency hearing, a higher CF and a smaller CR are required in their hearing aids. If listeners have sloping hearing loss that affects even mid- to low-frequency regions, a lower CF and a larger CR are needed in their hearing aids.

3. The efficacy of NLFC on listeners' perceptual ability

Compared to other types of frequency lowering schemes, NLFC provides a greater amount of acoustic information within a restricted frequency range and allows the accessibility of high-frequency information to HI listeners. Recent studies revealed that NLFC lowered the detection or discrimination threshold in some consonants, like /t/ or /s/, using either subjective measures such as perceptual responses (Picou et al., 2015) or objective measures such as cortical auditory evoked potentials (Zhang et al., 2014; Ching et al., 2016). Many studies quantified the change of audibility with NLFC using

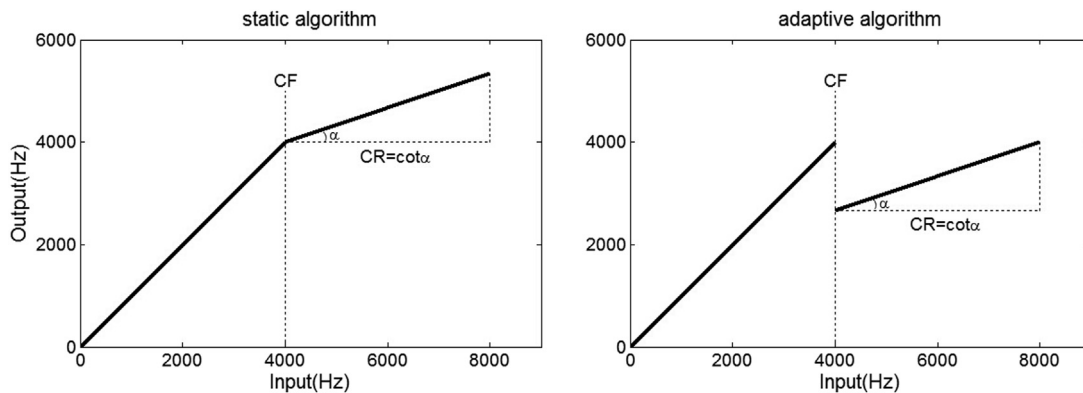


Fig. 2. Two SoundRecover (SR) nonlinear frequency compression algorithms. The left and right panels represent the first and the second generations of SR (i.e., SR-1 and SR-2), respectively.

the speech intelligibility index (SII). SII calculates the proportion of the signal that is audible based on the sensation level of the hearing-aid-processed speech in a number of discrete frequency bands for a particular HI listener. [McCreery et al. \(2014\)](#) adopted a modification of the SII and showed that 34 of the 36 listeners with mild to severe sensorineural hearing loss had a small increase in audibility with NLFC as compared with the conventional processing (CP). Similarly, [Perreau et al. \(2013\)](#) found that the detection threshold improved in hearing aid users with a moderate or moderate-to-severe hearing loss when they used NLFC. The threshold difference between NLFC and CP was between 0.005 and 0.087 in terms of SII, or between 10 and 35 dB when measured by sound field testing. A more recent study by [Wolfe et al. \(2015\)](#) also showed positive results with the NLFC and improvement of detection threshold. However, some researchers found inconsistent or conflicting results. [Bentler et al. \(2014\)](#) used SII to evaluate the audibility in 66 children with a mild to severe hearing loss, all of whom had used hearing aids with either NLFC or conventional amplification for at least 6 months. No significant difference in audibility was found between these two options.

At issue is whether the potentially improved audibility and lowered speech detection threshold as a result of NLFC will lead to better speech perception. In the following sections, we review the literature on the effects of NLFC on speech perception, subjective judgment of speech sound quality, and music perception. [Table 1](#) provides a concise summary of the studies on the efficacy of NLFC on speech perception.

3.1. NLFC and vowel perception

It is widely acknowledged that vowel identity is characterized by its formant pattern which varies as the tongue position changes. For adult speakers, the first two formants are normally below 3000 Hz. The relative positions of the first two formants play a vital role in vowel perception. HI listeners have reduced frequency selectivity but the formant excitation patterns in the cochlea are still clearly visible even when the auditory filters are four times broader than normal, a condition found in severe cochlear hearing loss ([Moore, 1998](#)). Unless the hearing loss becomes too severe, vowel perception is generally not a problem in HI listeners ([Edwards, 2004](#)). Therefore, when NLFC is applied to hearing aids, the goal is to maintain vowel perception performance at the level of CP.

[Glista et al. \(2009\)](#) examined consonant and vowel recognition in both HI children and adults. In this study, NLFC was set individually so as to ensure the best performance in a group of listeners with a sloping severe-to-profound high-frequency hearing loss. The subjects experienced an average period of 10 weeks for NLFC adaptation before the test. The results revealed that there was no significant difference in vowel recognition between NLFC and CP. In another study by [Perreau et al. \(2013\)](#), 17 postlingually deafened adults with hearing aids or hearing aids combined with cochlear implants were tested for consonant and vowel perception in quiet. The participants alternatively used NLFC or CP equipped hearing aid on a daily basis for a two-month period. The results

showed significantly lower vowel perception accuracy with NLFC than with CP after 2 months, which, the authors assumed, might be caused by less distinguishable formant structures due to the severe compression. This finding suggests that the impact of NLFC on vowel recognition is limited. In certain situations, NLFC may have detrimental effect on vowel perception when the vowel formants are severely compressed.

3.2. NLFC and consonant perception

Unlike vowels that are characterized by formant structure below the 3000 Hz region, consonants have distinct articulatory mechanisms and acoustic-phonetic characteristics. Sonorants such as nasals, liquids, and glides have vowel-like formant structures with spectrum energy predominantly distributed in relatively low frequency regions. By contrast, some types of obstruents, such as fricatives and affricates, are characterized by turbulent noise manifested as acoustic energy distributed along the entire frequency range on the spectrum. Fricatives produced with a more front articulatory constriction have a higher frequency of energy concentration. For example, the alveolar fricatives /s/ and /z/ have a spectral peak around 8000 Hz and palatal fricatives /ʃ/ and /ʒ/ have a spectral peak around 4000 Hz ([Jongman et al., 2000](#)).

High-frequency components greatly contribute to speech intelligibility. In English, fricatives provide essential cues for the differentiation between singular and plural nouns. The deprived accessibility to high frequency information has detrimental impact on speech recognition. Previous studies have revealed that removal of high-frequency components in speech signals results in confusions among the perception of various fricatives such as /s/, /ʃ/, /θ/, and /f/ ([Miller and Nicely, 1955](#); [Stelmachowicz et al., 2001](#)). Given that the majority of people with hearing loss have poor audibility in the high-frequency regions, restoring high-frequency audibility has always been an important goal of contemporary hearing-aid techniques.

Through compressing and shifting high-frequency acoustic energy to an audible low frequency area, NLFC extends the audible area and enables the accessibility of high-frequency information. This strategy may be particularly beneficial for consonant perception. However, previous studies yielded inconsistent results on the efficacy of NLFC on consonant perception in HI listeners. Favorable effects of NLFC were reported in [Wolfe et al. \(2010, 2011\)](#), [McCreery et al. \(2014\)](#), and [Alexander et al. \(2014\)](#). In [Wolfe et al. \(2010, 2011\)](#) studies, the recognition rate of some high-frequency consonants (including /s/ and /d/), as well as plural identification accuracy, displayed a more notable improvement with NLFC than without it after a six-week adaptation period in a group of school-age children with moderate to moderately-severe hearing loss. After six months of use, the benefits of NLFC maintained or increased further. The perception of /t/ was significantly better when NLFC was on than when it was off. [McCreery et al. \(2014\)](#) examined word recognition in HI adults and children with NLFC or CP. The results showed higher recognition accuracy with NLFC than with CP in both

Table 1
Summary of studies on speech perception using NLFC in hearing aids.

Authors & year	Participant information	Etiology of hearing loss	Stimuli and presentation level	Design	Acclimatization	Outcome measures	The FL parameters	Major findings
Sakamoto et al., 2000	11 adults (45–80 yrs) with severe-to-profound hearing loss participated NLFC satisfaction subjective assessment; 5 of them were tested for speech recognition test; 3 of them were tested for sentence recognition	10 acquired, one congenital	Subjective evaluation; Disyllabic Japanese words and nonsense monosyllables at 65 dB SPL; Japanese sentences at 70 dB SPL	NLFC with optimum setting vs frequency compression with Mode N setting vs participants' own hearing aids	1–2 wks	Satisfaction with the device speech recognition; sentence recognition	Individually fitted	5 out of 11 participants preferred NLFC fitted hearing aids. No significant improvement in speech recognition score with NLFC. All three participants showed improved audio-visual recognition scores with NLFC.
Simpson et al., 2005	17 adults with moderate-to-severe SNHL and sloping audiograms	Variable causes	CNC words at 55–60 dB A	NLFC vs conventional device	4–6 wks	Recognition of monosyllabic word	Same compression setting for all participants	8 participants showed improved recognition accuracy with NLFC and 1 participant showed worse performance with NLFC than with conventional device.
Simpson et al., 2006	7 HI adults (33–75 yrs)	Variable causes	CNC monosyllabic words at 55–60 dB A; VCV, CUNY sentences at 65 dB A; questionnaire	NLFC vs. conventional device	4–6 wks	Word recognition in quiet; consonant recognition in quiet; open-set CUNY sentences in noise APHAB self-assessment	Same frequency compression slope for all participants	No significant difference between NLFC and CP on recognition of words and consonants in quiet. One listener showed improved performance of sentence recognition in noise with NLFC. 6 out of 7 participants preferred the sound quality with CP.
Glista et al., 2009	11 HI children (6–17 yrs) 13 HI adults (50–81 yrs) Both groups with sloping high frequency hearing loss	Variable causes	Ling six-sound test; A modified version of UWO-DFD for consonant recognition, A plural recognition task for /s/ and /z/ , hVd for vowel recognition; Varied presentation level with the minimum testing level at 50 dB SPL	A withdrawal study composed of Acclimatization phase (CP), NLFC phase, multimemory phase (NLFC) and withdrawal testing (CP)	3 wks to 1.3 yrs for real world trial with NLFC and 2 wks to 5 mo real world trial with user selectable NLFC	Speech sound detection; Speech recognition; Self-reported preference measures	Individually fitted	Improved speech sound detection threshold, consonant and plural recognition with NLFC. No significant change in vowel recognition. NLFC benefits varied with listeners' age, degree and configuration of hearing loss.

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Table 1 (continued)

Authors & year	Participant information	Etiology of hearing loss	Stimuli and presentation level	Design	Acclimatization	Outcome measures	The FL parameters	Major findings
Bohnert et al., 2010	11 adults (17–76 yrs) with severe to profound hearing loss	Congenital or progressive hearing loss	OLSA with background noise presented at constant 65 dB and varied level for speech signal, Spontaneous acceptance questionnaire and real life test questionnaire	Listeners' own devices vs NLFC at 2 wks, 4 wks, 3 mo and 4 mo.	Up to 4 mo	Speech comprehension	Individually fitted	Seven out of 11 participants showed improved speech comprehension in noise with NLFC. Four out of 11 did not benefit from NLFC. Participants showed increased level of satisfaction after 2 and 4 mo of NLFC usage.
Wolfe et al., 2010, 2011	15 children (6–12 yrs) with mild to moderate low frequency hearing loss and moderate to moderately-severe high frequency hearing loss	N/A	Warble tones centered at 4k, 6k, and 8 kHz; /s/, /f/ phonemes; UWO Plural Test at 50 dB A and Phonak logatom test at 80 dB A for calibration procedure; BKB-SIN sentences at 50 dB HL	Within-subject design NLFC-off 6 wks, NLFC-on 6 wks, NLFC-on 6 mo	6 wks and 6 mo	Aided threshold assessment, recognition of speech sounds Phoneme discrimination; Speech recognition in noise	Individualized fitted	NLFC significantly improved aided thresholds in quiet and recognition of speech sound in quiet and noise. NLFC also improved speech recognition in noise after a certain period of usage.
Glista et al., 2012	6 HI teenagers (11–18 yrs), 5 had symmetrical high-frequency losses within 10 dB and one had asymmetrical hearing loss.	N/A	Adaptive, computer-controlled version of the Ling Test; The UWO Plurals Test at 55 dB SPL, nonsense CV pairs and UWO-DFD for consonant recognition at 55–70 dB SPL	Single subject design; Each participant was tested in baseline (CP), treatment (NLFC) and withdrawal (CP) phases	4 mo	Speech sound detection; Plural recognition; /s-/f/ discrimination; Consonant recognition	Individually fitted	The benefit of NLFC acclimatization varied across listeners. Not all children showed improved speech recognition outcome with post NLFC acclimatization.
McCreery et al., 2013	20 NH adults	N/A	CVC nonsense words with 9 fricatives and affricates in either initial or final position at 65 dB SPL	Used 3 audiograms to create processing conditions with varying high frequency audibility: CP vs. default NLFC settings vs. optimized NLFC settings	No	Fricative and affricate recognition	Fixed parameter for all participants	Recognition accuracy improved with increased audibility and bandwidth. Optimized SF and CR for audibility maximized nonword recognition accuracy.
Parsa et al., 2013	Study 1: 46 listeners divided into NH adults (12, 21–27 yrs), NH children (2, 8–18 yrs); HI adults (13, 50–81 yrs) and HI children (9, 8–17 yrs) Study 2: 8 HI adults and 12 NH adults	Various causes	Study 1: IEEE Harvard sentences at 65 dB SPL Study 2: speech samples in quiet by male and female speakers, speech samples in noise with 6 dB SNR by male and female speakers, a contemporary music sample (Beatles) and a classical music sample (Handel)	Study 1: Using MUSHRA paradigm Processed experimental stimuli with various NLFC settings Study 2: similar to study 1	No	Study 1: Sound quality rating Study 2: subjective sound quality rating	HI listeners fitted individually	HI listeners were more tolerant to the sound quality changes caused by NLFC than NH listeners. CF has more impact on sound quality rating than CR. HI children were more sensitive to the sound quality change caused by NLFC in comparison to HI adults.

Perreau et al., 2013	17 adults (39–82 yrs) with a cochlear implant and hearing aid or two hearing aids	Variable causes but not congenital	8-loudspeaker everyday sounds localization test; Multiple Jammer spondee-in-noise test, /iCi/, /hVd/ at 70 dB SPL	NLFC vs. CP	2 mo	Sound localization, speech perception in noise; consonant and vowel perception in quiet; Spatial Hearing Questionnaire; Sound Quality Questionnaire	Individualized fitting	No significant differences between NLFC and CP on sound localization or consonant recognition. Listeners performed worse on spondee-in-noise and vowel perception with NLFC than with CP.
Alexander et al., 2014	24 NH adults (18–50 yrs) 24 HI adults (18–74 yrs) ≤40 dB HL for frequencies ≤ 1 kHz and 45–70 dB HL for frequencies ≥ 3 kHz	Acquired	Fricative and affricate presented in/iC/context produced by 3 female talkers, mixed with speech-shaped noise at 10 dB SNR; Stimuli were presented with most comfortable level for each subject	FT in 4 conditions: FT-off, FT, WB, FT-off and noise reduction activated NLFC in 4 conditions: NLFC-off, NLFC, WB, SED	No	Consonant recognition	Fixed parameters for everyone	Both NH and HI listeners showed worse performance with FT. HI listeners performed better in the WB than in FT-off. HI listeners performed better in the WB and SED than in NLFC-off.
McCreery et al., 2014	24 adults (19–65 yrs) and 12 children (8–16 yrs) with mild to severe hearing loss	N/A	300 monosyllabic words composed of one of nine fricative/affricates in six vowel contexts at the initial or final position at 60 dB SPL.	CP vs. NLFC	No	Word recognition in noise	Individualized fitting	Improved audibility resulted in improved word recognition with NLFC in comparison to CP. NLFC did not introduce preferential benefit in word recognition in children than in adults.
Hopkins et al., 2014	46 adults with sloping hearing loss (47–92 yrs) varied in severity from mild to severe	N/A	10 consonants embedded in/aCa/syllables and ASL sentences at 65 dB SPL	NLFC-on vs. NLFC-off	1–121 wks experience with NLFC before testing	Consonant recognition and speech recognition in noise	Individualized fitting	NLFC facilitated consonant recognition but not speech recognition in noise. There was no significant correlation between duration of NLFC experience and recognition improvement.
Hillock-Dunn et al., 2014	17 children (9; 4–17; 1 yrs) with mild to profound bilateral sensorineural hearing loss	N/A	12 consonant phonemes in/Ci/syllables at 70 dB SPL; 25 spondees or words presented with two-talker speech or speech-shaped noise at 65 dB SPL for the targets and 50 and 55 dB SPL for initial presentation levels of the two-talker and speech-shaped noise masker	NLFC-on vs. NLFC-off	No	Consonant identification in quiet; Spondee identification	Individualized rationale	No significant differences between NLFC-on and NLFC-off for consonant identification or spondee identification. Participants experienced no difficulty identifying high-frequency consonant/s when NLFC was deactivated.
John et al., 2014	7 children (6–13 yrs) with cookie-bite audiometric configuration, normal hearing or mild hearing loss at 6–8 kHz	N/A	Warble tones at 4k, 6k, and 8 kHz; UWO Plurals Test at 50 dB A, UWO-DFD Test at 60 dB A, PPT at 70 dB A; BKB-SIN Test at 50 dB HL	3 conditions: wideband vs. NLFC-on vs. NLFC-off	4–6 wk trial of each condition	Aided sound field-threshold; Consonant detection and recognition; Speech recognition in noise	Individually fitted	No significant difference among the three conditions across all tested measures.

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Table 1 (continued)

Authors & year	Participant information	Etiology of hearing loss	Stimuli and presentation level	Design	Acclimatization	Outcome measures	The FL parameters	Major findings
Picou et al., 2015	17 adults (49–72 yrs) with sloping, symmetrical, mild to moderate sensorineural hearing loss	N/A	Adaptive Logatom Test at 70 dB A starting level; ORCA-NST test (32 CVCVC nonsense words) at 55 dB A; CST at 55 dB A for speech and 53 dB A for noise for sentence recognition and 65 dB A for sound quality rating; A Bonnie Raitt song at 70 dB A	CP vs. NLFC	3–4 wk trial period	Consonant discrimination threshold; Consonant recognition; Sentence recognition; Sound quality	Individualized fitting	The discrimination threshold for the consonant /s/ decreased when NLFC was activated. No significant difference was found between CP and NLFC on other measures.
Wolfe et al., 2015	11 children (7.4–13.2 yrs) with mild-to-moderate SNHL	N/A	UWO PT at 50 dB A, UWO-DFD Test, PPT at 70 dB A; /sh/low, /sh/high, /s/low and /s/high stimuli; BKB-SIN Test at 50 dB HL	3 conditions: wideband vs. NLFC-on vs. NLFC-off	4–6 wk trial	High frequency speech detection and recognition; Speech recognition in noise	Individualized fitting	Detection and recognition of high frequency stimuli were improved with NLFC. Speech recognition tested by UWO PT or UWP-DFD and sentence recognition in noise did not show significant difference across tested conditions.
Chen and Chan, 2016	18 NH listeners (≥19 yrs)	N/A	MHINT sentences at most comfortable level for each subject	NLFC vs. LFC	No	Sentence recognition	Fixed parameters for everyone	Listeners showed higher recognition accuracy for NLFC processed sentences than for LFC processed sentences. The degree of compression greatly affects the intelligibilities of FC processed sentences. SF lower than 2.2 kHz with high CR reduced phoneme recognition.
Alexander, 2016	14 MS adults (47–83 yrs) ≥ 60 dB HL at 6 and 8 kHz 14 MM adults (27–82 yrs) ≥ 30 dB HL and ≤60 dB HL at 6 and 8 kHz	N/A	60 VCV syllables (of 20 consonants each embedded in 3 vowel contexts) 12 /hVd/ syllables 7 fricatives and 2 affricates in /iC/ syllables; Stimuli presentation level varied but lower than 105 dB SPL	NLFC with 6 SF*CR combinations and one control condition	No	Consonant and vowel recognition	Fixed parameters for everyone	CR exerted greater influence for low SFs than for high SFs. NLFC significantly improved final /s/ and /z/ identification for both groups of HI listeners.

APHAB: Abbreviated Profile of Hearing Aid Benefit; ASL: adaptive sentence list; BKB-SIN: Bamford-Kowal-Bench speech in noise sentences; CF: cutoff frequency; CNC: consonant-nucleus-consonant; CP: conventional processing; CR: compression ratio; CST: connected speech test; CUNY: City University of New York; FC: frequency compression; FT: frequency transposition; FL: frequency lowering; HL: hearing level; HI: hearing impaired; LFC: linear frequency compression; MHINT: Mandarin hearing in noise test; NLFC: nonlinear frequency compression; NH: normal hearing; N/A: not available; OLSA: the Oldenburger sentence test; ORCA-NST: The Office of Research in Clinical Amplification Nonsense Syllable Test; PPT: phoneme perception test; PTA: averaged pure-tone threshold; SED: spectral envelope decimation; SF: start frequency; SRT: speech reception threshold; UWO-DFD: The University of Western Ontario Distinctive Features Differences Test; UWO PT: The University of Western Ontario Plural Test; WB: wideband.

adults and children. Alexander et al. (2014) recruited 12 adult hearing-aid users and the average perception rate of fricatives and affricates in the NLFC-on condition was 72.4%, significantly higher than the average score of 67.1% in NLFC-off condition. The listeners who performed worse with NLFC-off tended to benefit more with NLFC-on. While Hopkins et al. (2014) also demonstrated the benefit of using NLFC in consonant recognition, the authors found no further benefit as a result of acclimatization, at least for the HI adults. Moreover, the benefit seemed to be negatively related to the high-frequency threshold.

Although there exist positive findings in the previously stated studies, there are some inconsistent results in the literature. Perreau et al. (2013) recruited 17 adults with moderate or moderate-to-severe hearing loss and tested their perception on consonants monaurally in quiet. The Iowa Consonant Recognition Test, which included thirteen consonants (d, v, k, g, n, f, s, sh, t, m, z, p, z), was used. The results showed no significant difference between NLFC and CP in consonant recognition scores after two months of listening experience. In addition, no improvement was found between each of the two conditions from their baseline performance, respectively. Glista et al. (2012) evaluated the speech perception using consonant and plural recognition tests in six older children aged between 11 and 18 years old. Some of the children's performance improved with a prolonged use of NLFC while other children's scores remained stable over the time course of the evaluation. Hillock-Dunn et al. (2014) examined speech perception performances in 17 pediatric full-time hearing aid users between the ages of 9 and 17 years old. The user's ability to identify consonants in quiet and in noise was tested with NLFC on and off conditions. For a baseline figure, the children were first tested using their personal hearing aids before being tested with laboratory versions of Phonak Naida V SP hearing aids. This study found no significant difference between the NLFC on and off conditions in the factory hearing aids in either quiet or noise condition. Most of the participants within this study had the ability to recognize /s/ regardless of whether or not they were in the NLFC on or off condition, which contradicts previous research in which users had difficulty identifying high-frequency fricative consonants. The results from Hillock-Dunn et al. (2014) showed that NLFC neither harmed nor aided speech perception in hearing aid users, however, the fact that individuals with a more robust form of the NLFC algorithm in hearing aids did better in consonant perception suggests that further research is needed to examine the potential benefits of NLFC in hearing aids.

3.3. NLFC and sentence perception

There are not many studies focusing on the efficacy of NLFC at the sentence level. Speech perception at sentence level is a more complicated procedure than phoneme recognition, as it requires more involvement of the central auditory system and cognitive function (Friederici, 2012). Sakamoto et al. (2000) studied the sentence recognition in three severe-to-profound HI adults with hearing aids fitted with

NLFC. Three test modes (i.e., audio-visual, audio only, and visual only) were used. In the audio only mode, one subject performed better with NLFC than with CP, one performed worse, and the other one did not repeat any key words at all in either hearing aid fitting. However, when tested in the audio-visual mode, all three subjects performed significantly better with NLFC than with CP. Note that there was no time for adaptation to the NLFC. Such a small sample size ($N = 3$) made it difficult to implement any statistical analysis. In addition, the authors did not explain explicitly the influence of visual cues or lip-reading on the efficacy of NLFC.

Some researchers evaluated the sentence perception ability with NLFC in competing noise using speech reception threshold (SRT) as the outcome measurement. For example, Simpson et al. (2006) investigated the sentence perception in eight-talker babble masker. Five HI adults, all of whom had a steeply sloping profound high-frequency hearing loss, were given a period of 4–6 weeks for NLFC acclimation. Only one out of five subjects displayed a significantly lower threshold with NLFC than with CP. Although the group mean SRT with NLFC was significantly lower than that with CP, the data lacked statistical verification due to the small sample size. Bohnert et al. (2010) compared the SRT of the Oldenburger Sentence test in 11 HI listeners using their personal hearing aids followed by NLFC fitted device (i.e., SR-1 with Phonak hearing instrument) up to a 4-month period. The Oldenburger Sentence test consists of non-sense sentences, each of which is composed of 5 real words (name–verb–number–adjective–object). The authors found that seven participants showed a reduced SRT (i.e., improved speech perception) and the other four participants showed an increased SRT (i.e., deteriorated speech perception) after 4 months of NLFC use. Wolfe et al. (2011) performed a follow-up study on 15 HI children whose hearing loss ranged from mild to moderate in the low frequencies and moderate to moderately-severe in the high frequencies. In the 6-week test session (Wolfe et al., 2010), no significant difference was found in SRT between the NLFC-on and NLFC-off conditions. However, in the 6-month test session (Wolfe et al., 2011), investigators found that the group average SRT was significantly lower with the NLFC-on than with the NLFC-off condition. When a repeated-measures design was applied, the results showed that long-term use of NLFC produced promising performance. John et al. (2014) and Wolfe et al. (2015) tested SRT using BKB-SIN sentences in children with either cookie-bite audiograms or mild-to-moderate sensorineural hearing loss. However, both studies showed no significant difference across NLFC-on, NLFC-off, and wideband conditions.

3.4. Effects of NLFC on speech sound quality

The majority of research effort focused on the identification or recognition of individual speech sounds using various signal processing techniques. Few studies examined how the sound quality has been changed with the adaptation of NLFC. Although a sound could be accurately recognized with an uncomfortable or unnatural auditory sensation, sound quality is nonetheless an important property that a hearing aid user

cares tremendously and should receive more research attention. Sound quality can also be utilized as a cue for speaker's gender, age, etc.

Simpson et al. (2006) and Picou et al. (2015) adopted self-assessing subjective measures to evaluate listeners' satisfaction with the sound quality using NLFC or conventional devices. Both studies showed no improvement in perceived sound quality associated with NLFC. By contrast, Bohnert et al. (2010) reported increased satisfaction of sound quality in 8 out of 11 HI listeners over a 4-month usage of NLFC. Parsa et al. (2013) recruited adults and children, either with hearing loss or with normal hearing, and asked them to rate the quality of speech in quiet, speech in noise, and music after processing with a different set of NLFC parameters. The results showed that NLFC did have an impact on the perceived sound quality and the change of CF had more impacts on sound quality ratings than did the change of CR. Additionally, the HI adults were more tolerant to increased CR than their NH counterparts. These findings suggested that speech sound quality was not substantially affected in a certain range of NLFC settings for HI individuals.

3.5. The efficacy of NLFC on music perception

One cannot emphasize enough the importance of music appreciation to the quality of life. The acoustics of speech and music bear enormous differences in aspects such as dynamic range, spectral nature, etc. (Chasin and Russo, 2004; Chasin, 2012). The input dynamic range for music is near 80 dB whereas that for speech is usually around 40 dB. In the spectral domain, all musical instruments (with exception for percussion instruments such as a drum) produce a fundamental frequency (F0) and many harmonics that are multiples of the F0. Although speech also produces an F0 with multiple harmonics, the harmonics in musical instruments are usually much stronger in intensity and extended farther along the spectral axis than those of vowels in speech. Some instruments can produce robust harmonics as high as 10 kHz. High harmonics of musical notes are helpful for the listeners to distinguish the sound of one instrument from another (i.e., timbre) (Gfeller et al., 2002; Jung et al., 2012). Frequency lowering techniques including NLFC might disrupt the harmonic relationship in the signal and would have detrimental effects on music perception.

Few studies focused on the influence of NLFC on music perception but the interest in this field has been increasing over the past few years. Uys et al. (2012) completed a comprehensive investigation on music perception in 40 adults who had a moderate to severe hearing loss and wore hearing aids. The prototype hearing aid used in their study was the Phonak Naida III Ultra Power which adopted the NLFC algorithm. By using a music perception test and subjective outcome measurements, four aspects of music (i.e., rhythm, timbre, pitch, and melody) were evaluated. A period of four weeks or more was taken to acclimatize the subjects with their hearing devices. The results indicated that timbre and melody, but not pitch or rhythm, improved with NLFC than without it.

Additionally, the use of NLFC also improved the music qualities of overall fidelity, tinniness, and reverberance. For the property of naturalness, no improvement was found. Music quality perceived through NLFC was also investigated in Parsa et al. (2013) and Mussoi and Bentler (2015). Consistent with the results of Uys et al. (2012), both studies found that the quality of music was not significantly degraded as long as the NLFC setting was not too strong. Interestingly, the hearing aid users' rating of sound quality of music with NLFC was generally higher than that of participants with NH who listened to the NLFC-processed music (Parsa et al., 2013). Among hearing aid users, the HI listeners without music training rated a higher preference score for the music passages with maximum compression than did the musically-trained HI listeners (Mussoi and Bentler, 2015). Note that the participants in the Parsa et al. (2013) and Mussoi and Bentler (2015) did not have auditory acclimatization. Future investigation on the long-term effects of NLFC on music perception is needed.

4. Factors accounting for NLFC efficacy

The previous section presented inconsistent outcomes regarding the efficacy of NLFC on the perceptual abilities in HI listeners. Alexander (2013) proposed a list of extrinsic and intrinsic factors that might account for individual differences in speech recognition with various types of frequency lowering techniques. The present paper focused only on NLFC. In the following section, we will discuss the relevant factors (i.e., NLFC settings, time-course of acclimatization, listener characteristics, and perceptual tasks) that might account for the inconsistent outcomes.

4.1. NLFC settings

Unlike other types of frequency lowering techniques, NLFC selects a CF to nonlinearly compress the frequency components above the CF and meanwhile maintain the frequency components below the CF unprocessed. The CF and CR jointly determine the output frequency range and degree of compression. Parsa et al. (2013) and Mussoi and Bentler (2015) examined the effect of varied NLFC settings on sound quality rating of speech and music in both NH and HI listeners. Both studies revealed that both NH and HI listeners showed less preference for speech and music stimuli with a stronger compression. Alexander (2016) conducted a systematic examination on the influence of start frequency (SF) and input bandwidth (BW) on the recognition of speech segments in HI listeners with mild to moderately severe hearing loss. The subjects in that study were divided into two groups, one with mild to moderate high-frequency hearing loss (MM) and one with moderately severe high-frequency hearing loss (MS). For the MM participants, the SF was set at 1.6, 2.8, and 4.0 kHz and the input BW was set at 7.1 and 9.1 kHz. For the MS participants, the SF was set at 1.6 and 2.2 kHz and the input BW was set at 5.0, 7.1, and 9.1 kHz. The CR for each setting varied from small CR corresponding to low SF and narrow input BW to large CR corresponding to high SF and

wide input BW. The results revealed that the outcomes with regard to the NLFC efficacy were mainly determined by its settings. In particular, speech intelligibility decreased when the SF was lower than 2.2 kHz with a high compression CR. The SF exerted more influence than the CR. The author pointed out that “no one set of parameters simultaneously maximizes recognition for all tokens; the optimal settings for individual phonemes may vary according to their acoustic characteristics (p. 956).”

In practice, the hearing aid devices should be programmed and fitted individually for HI listeners. Generally speaking, compared to listeners with mild hearing loss, listeners with more severe hearing loss have limited audibility to a smaller frequency range. Accordingly, the hearing aids are programmed with a lower CF and a relatively higher CR to ensure better accessibility to a greater range of frequency components. For patients with severe hearing loss, NLFC with aggressive settings likely help them regain accessibility to frequency components that are not audible without the device. Therefore, even though the aggressive settings exert a greater influence on the acoustic characteristics of speech sounds, they still benefit from NLFC in comparison to CP that amplifies selected frequencies that are not accessible to the patients at all. However, for the mild hearing-loss patients who have the audibility to a relatively wide frequency range that contains the main perceptual cues for speech recognition or maintain relatively good audibility to high-frequency components, the recognition accuracy is likely to be high without NLFC. Hillock-Dunn et al. (2014) compared consonant and spondee identification in 17 children with and without laboratory fitted NLFC. They used listeners' performance with personal hearing aids as the baseline measures. The results showed no significant improvement in the recognition accuracy with NLFC. When compared the NLFC parameters in the laboratory aids with participants' personal hearing aids, the authors found that listeners' personal aids with more aggressive NLFC settings than used in the laboratory aids resulted in better consonant identification accuracy in quiet.

4.2. Auditory acclimatization

Perceptual adaptation plays an important role in speech recognition in adverse listening conditions, with unfamiliar talkers or non-native speech materials, etc. (e.g., Bradlow and Bent, 2008; Erb et al., 2013; Trude and Brown-Schmidt, 2012). The role of perceptual adaptation has been a long-lasting debated topic in hearing aid research. NLFC, like other types of frequency lowering techniques, introduced new frequency components to the HI listeners. When fitted with these devices, listeners are likely to experience “a systematic change in auditory performance with time, linked to a change in the acoustic information available to the listener” (Arlinger et al., 1996, p. 87S). This process is defined as auditory acclimatization which “helps individuals adapt to altered sensory input to maintain optimum performance in their environment” (Alexander, 2013, p. 103). Among the reviewed articles, most studies recruited participants who had had used hearing aids

programmed with CP or other types of frequency lowering techniques for a certain period. However, not all studies allowed acclimatization to NLFC in their research paradigm. Some studies assured several weeks' usage or a trial period of NLFC prior to actual testing (John et al., 2014; Hopkins et al., 2014; Glista et al., 2009; Perreau et al., 2013; Picou et al., 2015; Simpson et al., 2006; Wolfe et al., 2015). For example, in Glista et al. (2009), the participants experienced up to 3 months trial phase with CP, which was followed by a real-world trial phase with NLFC ranging from 3 weeks to 1.3 years. The results showed improved high-frequency speech detection and recognition abilities. Hopkins et al. (2014) recruited participants who had at least four months experience with CP and a period of usage with NLFC ranging from 1 to 121 weeks. The result showed no evidence in favor of long period acclimatization for full benefit of NLFC. In some other studies (John et al., 2014; Perreau et al., 2013; Picou et al., 2015; Simpson et al., 2006; Wolfe et al., 2015), at least 3 weeks' experience with NLFC was ensured to help participants become familiar with the tested technique. However, no significant differences on the perceptual performance were found between CP and NLFC.

Some studies conducted follow-up examinations to test the change of recognition performance (Glista et al., 2012; Wolfe et al., 2010, 2011; Bohnert et al., 2010). Wolfe et al. (2010, 2011) tested participants with NLFC off for six weeks, NLFC on for six weeks and NLFC remained on for six months. The results showed improved plural recognition and consonant discrimination in quiet with NLFC than without NLFC and this improvement was maintained or increased from 6-week to 6-month testing phase. More importantly, the authors found that while the sentence recognition in noise did not show improvement over a 6-week period, it showed significant improvement after 6 months. This result suggested that even though the acclimatization may not be necessary for every aspect of speech recognition, it probably has impact on some high-level speech understanding. Bohnert et al. (2010) tested the SRT of sentence recognition and the level of satisfaction of device use from 11 HI listeners over a four month period. The authors found that seven participants showed improved SRT and eight participants experienced an increased level of satisfaction after 2-month and 4-month experiences with NLFC as compared to their personal devices. A little different from the group design in the above-mentioned studies, Glista et al. (2012) adopted a longitudinal single-subject design to evaluate the change of perceptual ability at the individual level. Each participant was tested with CP at week 6, 8, 10 in the baseline phase and NLFC at week 12, 14, 16, 18, 22, and 28 in the treatment phase, which were followed by a withdrawal phase of CP within 1–7 weeks post treatment session. The results showed varying outcomes with regard to the benefit of NLFC and the acclimatization effect across listeners.

According to these studies, a certain period of acclimatization of NLFC fitting may not benefit every HI listener. A relatively longer time of acclimatization phase seems improve at least some HI listeners' perceptual performance involving various aspects of speech processing skills. Distinct from the

procedures that amplify certain frequency components, frequency lowering techniques cause fundamental change of the acoustic profiles of speech segments. It is likely that listeners' auditory and higher level cognitive systems take a relatively long time to adjust to the modified acoustic characteristics induced by these techniques. Nonetheless, great individual variability in acclimatization effect has been observed, which may be associated with listeners' characteristics such as neurophysiological or cognitive functions.

4.3. Listener characteristics

Associated with the diverse etiology of hearing loss, age of hearing loss onset, and severity of hearing loss, HI listeners have different hearing aid experiences. John et al. (2014) investigated the effect of NLFC on a special population: children with cookie-bite audiometric configurations. NLFC normally shift high-frequency information to a lower frequency region. However, for this population, the frequency region where the high-frequency components are moved to is the region where a greater degree of hearing loss exists. The authors speculated that in addition to the reason that these children had normal or near-normal sensitivity to high frequencies, the greater hearing loss in mid-frequency region where the high frequencies are moved to likely undermines the benefit of NLFC.

Hearing aid is programmed individually to accommodate each listener's need. Listeners with mild hearing loss have audibility to a relatively wider frequency range. Correspondingly, they require less aggressive frequency compression. In contrast, for listeners with moderate to severe hearing loss, they have less accessibility to a much constricted frequency range. In this case, the hearing aid needs to be programmed with a relatively lower CF and a greater CR. As discussed earlier, the degree of compression directly affects the extent of modification of acoustic characteristics. It is reasonable to assume that listeners with different severity of hearing loss may have different magnitude of benefit from NLFC.

In addition to the personal variability related to the characteristics of hearing loss, the age difference may also exert influence on the outcomes of speech understanding with NLFC. Many researchers pointed out that adult-child difference may affect the magnitude of benefit with hearing aids. Compared to adult listeners, children especially young children have incomplete linguistic knowledge. On the other hand, given the continuing maturation of speech-hearing structures and developing cognitive abilities, researchers assume that children may experience greater benefit from frequency lowering techniques in comparison to adults. Among the above reviewed articles, some studies either recruited only children (Glista et al., 2012; Hillock-Dunn et al., 2014; John et al., 2014; Wolfe et al., 2010, 2011, 2015) or only adults (Alexander et al., 2014, 2016; Bohnert et al., 2010; Chen and Chan, 2016; Hopkins et al., 2014; McCreery et al., 2013; Mussoi and Bentler, 2015; Sakamoto et al., 2000; Simpson et al., 2005, 2006; Perreau et al., 2013; Picou et al., 2015; Uys et al., 2012). Among these studies, three out of six

studies involving pediatric HI listeners showed significant improvement in speech recognition with NLFC and two studies showed no significant difference between NLFC and CP. One study showed improved high frequency detection and recognition but no significantly different speech recognition on NLFC relative to CP. For those studies that recruited adult listeners, no consistent results of improved outcomes were found across all participants or all perceptual measures. That is, improved speech recognition was observed in certain participants in certain measures with NLFC. Other participants and other recognition measures did not show significant difference between NLFC and CP.

Some studies recruited both children and adults (Glista et al., 2009; McCreery et al., 2014; Parsa et al., 2013). Glista et al. (2009) found that children received a greater benefit from NLFC in plural recognition and had a stronger preference for NLFC in comparison to adults. Parsa et al. (2013) compared the rating of sound quality between NH and HI listeners including both children and adults. The authors found that HI children were more sensitive to the change of NLFC settings in that they gave different quality scores for stimuli with different frequency compression conditions but HI adults did not. Unlike Glista et al. (2009) and Parsa et al. (2013), McCreery et al. (2014) found no significant difference between HI children and HI adults. Note that the children in Parsa et al. (2013) study also participated in Glista et al. (2009, 2012) studies. The authors presumed that the great benefit and sensitivity in HI children might be associated with the developmental factors in children or high listening level used in children. In addition, the appropriate individualized NLFC setting might also provide more benefits to HI children than to HI adults. However, given the mixed results on the adult-children difference in NLFC outcomes, there still lacks solid evidence to show the greater benefit of NLFC in children.

4.4. Perceptual tasks

Speech perception is a multi-faceted task that includes listeners' subjective judgement of the sound quality, identification of individual sounds at phonemic level, recognition of meaningful words, and comprehension of sentence meaning. Among different types of speech sounds, fricatives and affricates are the two categories of consonants that are primarily cued by the spectral pattern of high-frequency components. Other types of speech sound such as vowels, nasals, glides, and stops are predominantly cued by spectral information distributed in relatively low or mid frequency regions. Therefore, it is reasonable to assume that if listeners' mid- and low-frequency audibility remains intact, the performance of speech recognition on vowels and other types of mid-frequency consonants may not show significant changes no matter what kind of hearing aid or programming technique is used. As most HI listeners have deficiency in accessing high-frequency information, the primary focus of hearing aids including NLFC is to help the listeners gain audibility to high-frequency components. Accordingly, the majority of hearing aid research evaluated the efficacy of auditory devices by

comparing performance of consonant recognition with or without the tested device or programming technique.

Most reviewed studies tested listeners' recognition of consonants in the form of nonsense words or syllables containing a number of English fricatives and affricates embedded in certain vowel contexts or plural test focusing on the discrimination of /s/-/ʃ/. Among these studies, 12 studies found positive evidence or at least partial positive evidence on certain participants in support of the improved consonant detection or recognition with NLFC than with CP. Five studies (Hillock-Dunn et al., 2014; John et al., 2014; Sakamoto et al., 2000; Simpson et al., 2006; Perreau et al., 2013) showed no significant differences between NLFC and CP. It is noteworthy that Simpson et al. (2006) used similar research paradigm as Simpson et al. (2005). Simpson et al. (2005) recruited 17 participants and found improved recognition in 8 participants. Simpson et al. (2006) only recruited 7 participants with more steeply sloping hearing loss and none of them showed significant differences in consonant recognition between NLFC and CP. Perreau et al., (2013) recruited participants who used both cochlear implants and hearing aids. The use of cochlear implant may introduce additional confounding factor for the evaluation of NLFC efficacy. The participants in Hillock-Dunn et al. (2014) were pediatric HI listeners who were not allowed a acclimatization period. The authors speculated that the lack of significant changes between NLFC on and off may be associated with the time course of acclimatization and the effectiveness of the listeners' compression settings. John et al. (2014) tested children who had normal or near-normal sensitivity to high-frequency components. These children showed ceiling level performance without NLFC.

Other than the consonant recognition, sentence recognition is a task more related to listeners' daily life speech understanding. In comparison to recognition of consonant and vowels, sentence recognition involves listeners' prior linguistic knowledge and higher-level cognitive processes. Previous literature suggests that listeners adopt more top-down processing in speech recognition in adverse listening conditions (Hannemann et al., 2007; Shahin et al., 2009; Warren, 1970). Therefore, it is likely that for HI listeners who suffered from acquired hearing loss in adulthood, the deficiency in high-frequency audibility may not detrimentally influence their comprehension of speech utterances. Therefore, the use of hearing aids may not dramatically influence their recognition accuracy of speech sentences.

In addition to the speech understanding of speech sounds and utterances, the subjective judgement of sound quality was only reported in a few studies (Bohnert et al., 2010; Parsa et al., 2013; Picou et al., 2015; Sakamoto et al., 2000; Simpson et al., 2006). Among these studies, two showed increased satisfaction with sound quality in certain participants or with a certain period of usage with NLFC. One showed no significant difference between NLFC and CP. One showed better sound quality ratings with CP than with NLFC. It is not surprising that the NLFC may not introduce positive influence on the sound quality rating due to distortion to the original speech signals. Parsa et al. (2013) revised the NLFC

settings of CF and CR and evaluated listeners' ratings of sound quality as a function of the parameter change. They found that CF exerts great influence on the sound quality rating. According to this finding, the HI listeners with more severe hearing loss may experience more negative influence of NLFC on the sound quality perception. In addition, the time-course of acclimatization may also play an important role in sound quality rating. As HI listeners have a longer experience with NLFC, they are more adapted to the sound quality of the new sensory input. This may explain the improved sound quality of NLFC in Bohnert et al. (2010) in which the participants had a 4-month experience with NLFC.

Other than the aforementioned factors, the gender difference in both listeners and speakers may also impact the auditory efficacy of NLFC. So far, there is little published data with regard to the gender difference of listeners on the NLFC efficacy. However, a couple of studies presented evidence showing the effects of talker's gender. Stelmachowicz et al. (2001) examined the recognition of low-pass filtered voiceless fricatives. The speech stimuli were recorded from an adult male, an adult female, and a child talker. Then, the voiceless fricative /s/ was selected and low-pass filtered with the cut-off frequency being systematically varied between 2000 and 9000 Hz. For the sound samples from the adult, female and the child, the performance of both the NH and the HI groups improved with the increase of the cut-off frequency up to 9000 Hz. Parsa et al. (2013) used speech stimuli from different male and female speakers and found significant interaction effects of processing setting by talker's gender in NH listeners. It is well known that adult speakers especially adult males have longer vocal tract than adult females and child speakers, which caused lower resonant frequencies in males than in females and children. The same frequency compression setting applied to male, female or child talkers may cause different results, which may influence listeners' recognition outcomes.

5. Summary

Nonlinear frequency compression (NLFC) is a technically innovative scheme used in modern hearing aid technology. Its primary goal is to provide high-frequency information in the speech signal by compressing it into the more audible low-frequency regions. The expectation of little detrimental effects of NLFC on vowel perception has been met as long as the compression does not involve very low frequency. The benefit of NLFC in consonant perception is not conclusive although the majority of current research provides at least partial positive evidence showing improvement of one or more tasks in consonant recognition of some participants with NLFC over CP. Long-term use of NLFC appears to be beneficial for sentence recognition although not all studies converge on the facilitative effect of NLFC on sentence recognition. Since NLFC might potentially distort the harmonic ratio in the original sound signals, it is important to evaluate its effects on sound quality and music appreciation. Limited research has indicated that NLFC seems to have no detrimental effects on sound quality appraisal and music appreciation of those with

impaired hearing who use this algorithm in their hearing aids. The inconsistent outcomes on the auditory efficacy of NLFC might be associated with compression parameter settings, time-course of acclimatization, different patient population (i.e., degree and configuration of the hearing loss), age of the patients (children versus adults), experience with the device, and perceptual tasks, etc. Small sample sizes are a common issue in studies reviewed here. Clearly, more rigorous research data are needed to further our knowledge on the potential benefit of NLFC. Such knowledge will help guide clinical rehabilitation of patients with precipitous high-frequency hearing impairment.

Conflicts of interest

None.

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